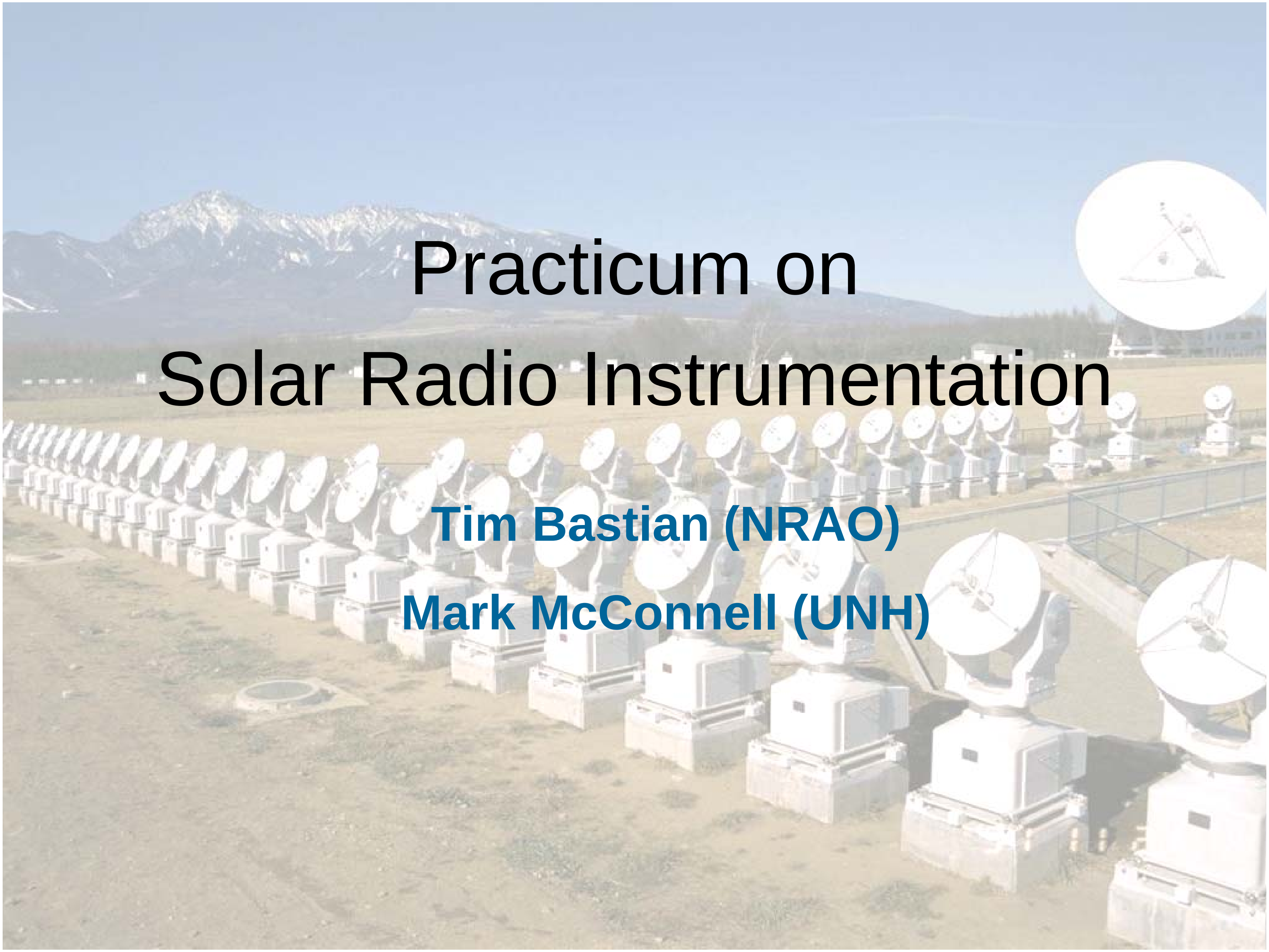


Practicum on Solar Radio Instrumentation

Tim Bastian (NRAO)

Mark McConnell (UNH)

Why observe the Sun at radio wavelengths?

- Solar emission at radio wavelengths provides unique diagnostics for physical parameters of interest and their evolution in time and space

  - thermal free-free - nonthermal gyrosynchrotron
  - thermal gyroresonance - plasma radiation
  - exotica

$$B(\mathbf{r}),\ T(\mathbf{r},t),\ f(\mathbf{r},\mathbf{p},\theta,t)$$

- Radio emission probes both optically thick and optically thin regimes
- Radio emission probes both active and quiet phenomena
- Radio emission probes all layers of the solar atmosphere from the temperature minimum to the interplanetary medium
  - temperature minimum to middle corona (ground)
  - middle corona to IPM (space)
- Radio waves can be observed with high angular (arcsec), temporal (ms), and spectral resolution (kHz)

Preliminaries

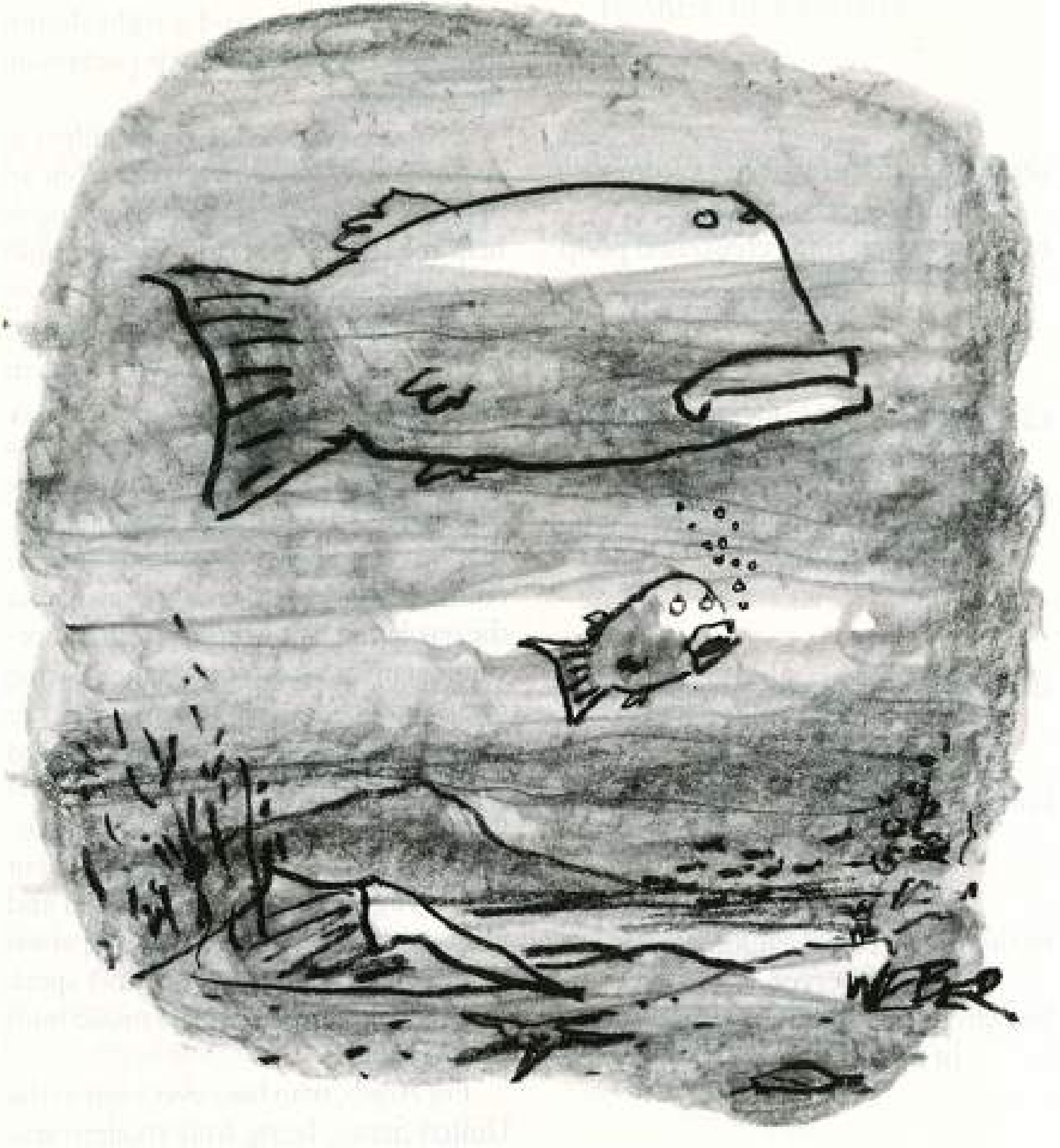
- No RF lab at NRH
- No easy way to transport receivers and test equipment to UNH
- However, UNH has a Small Radio Telescope (SRT)

Therefore, we'll do things in two parts today:

1. I will present basic concepts relevant to radio instrumentation (science issues and data analysis are deferred to my other two lectures)
2. We will then use the UNH SRT remotely to observe the Sun (Mark McConnell)

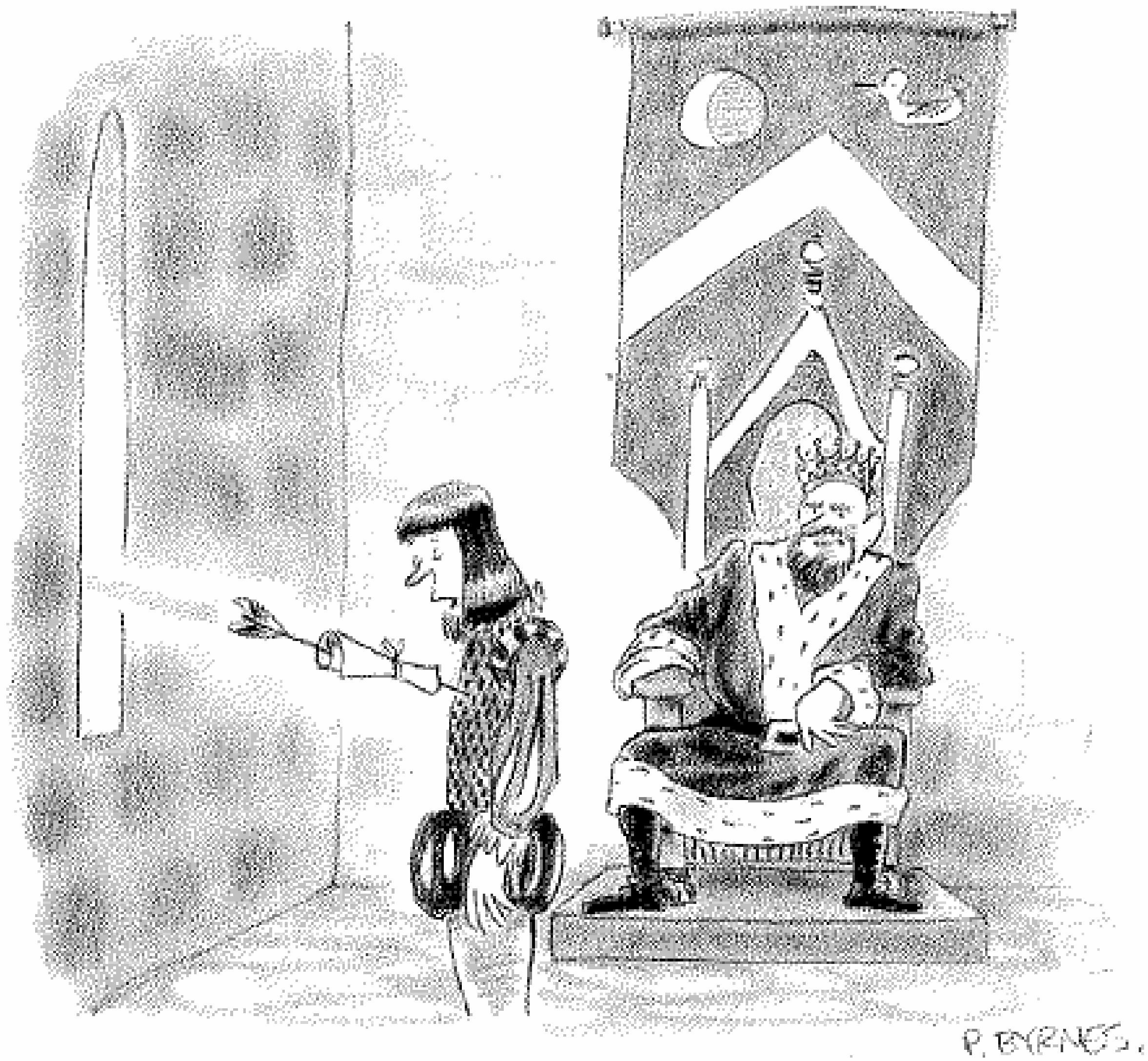
Practicum on Solar Radio Instrumentation

- The radio spectrum and its uses
- Terminology and some important concepts
- Overview of instrumentation on the ground and space
  - *antennas and receivers*
  - *single dish observing*
  - *interferometry*
  - *Fourier synthesis imaging*
- Examples
  - *radiometry and polarimetry*
  - *broadband spectroscopy*
  - *interferometry*
  - *Fourier synthesis imaging*
- Using the UNH SRT



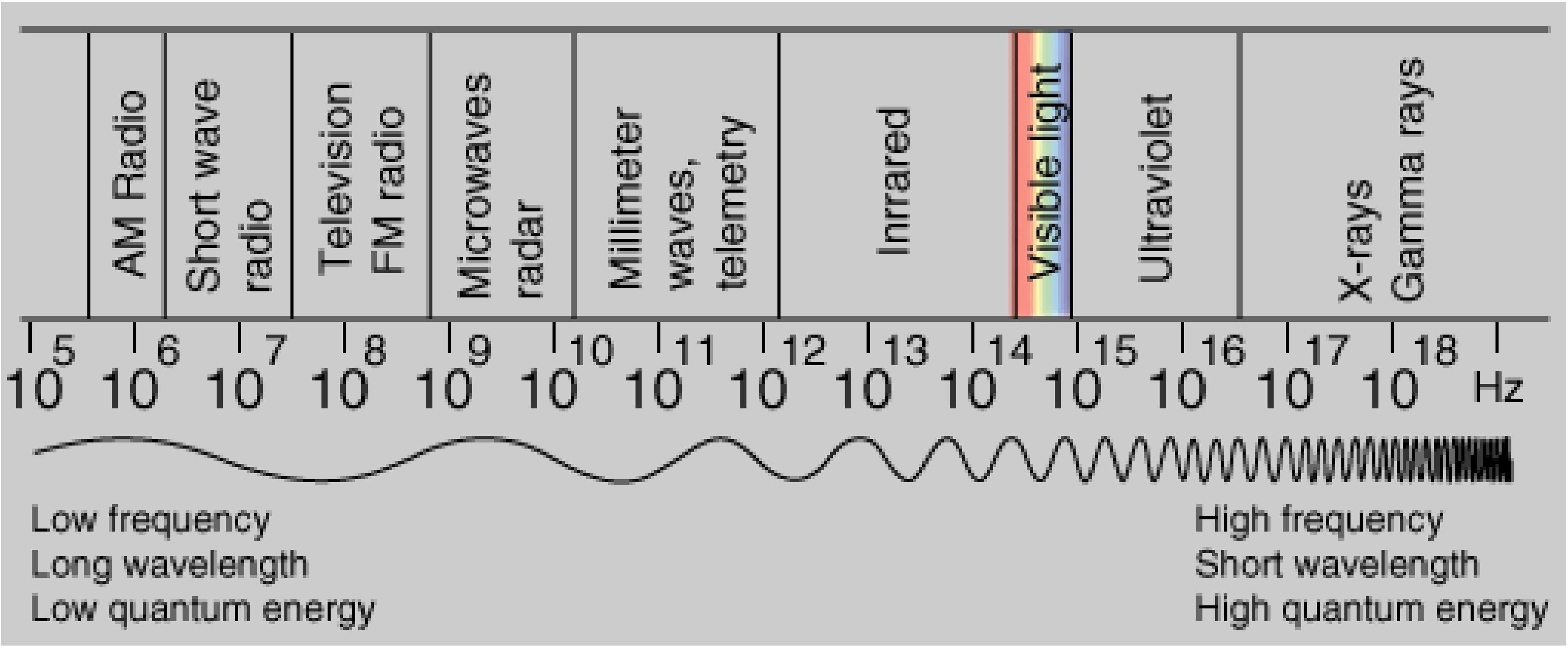
"Why is it so wet?"

tbastian@nrao.edu

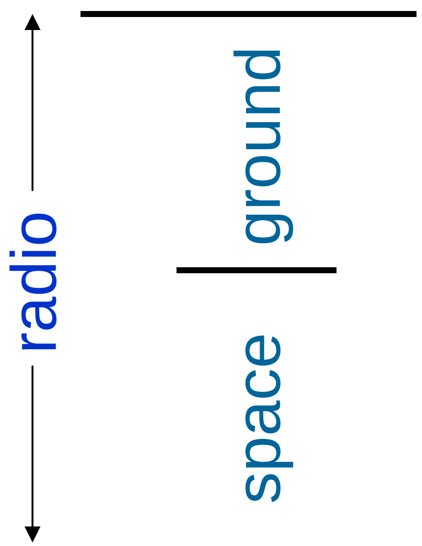


"Instant message, sire."

The electromagnetic spectrum



The electromagnetic spectrum



CLASS	FREQUENCY	WAVELENGTH	ENERGY
γ	300 EHz	1 pm	1.24 MeV
HX	30 EHz	10 pm	124 keV
SX	3 EHz	100 pm	12.4 keV
	300 PHz	1 nm	1.24 keV
EUV	30 PHz	10 nm	124 eV
NUV	3 PHz	100 nm	12.4 eV
NIR	300 THz	1 μm	1.24 eV
MIR	30 THz	10 μm	124 meV
FIR	3 THz	100 μm	12.4 meV
EHF	300 GHz	1 mm	1.24 meV
SHF	30 GHz	1 cm	124 μeV
UHF	3 GHz	1 dm	12.4 μeV
VHF	300 MHz	1 m	1.24 μeV
HF	30 MHz	1 dam	124 neV
MF	3 MHz	1 hm	12.4 neV
LF	300 kHz	1 km	1.24 neV
VLF	30 kHz	10 km	124 peV
VF	3 kHz	100 km	12.4 peV
ELF	300 Hz	1 Mm	1.24 peV
	30 Hz	10 Mm	124 feV

T. Bastian, Second SPD Summer School on High Energy Solar Physics

Radio Frequency Allocations

System	Frequency range
RFID systems	125 to 134 kHz 13.56 MHz UHF (400 to 930 MHz) 2.45 GHz 5.8 GHz
AM radio (United States)	535 kHz to 1.7 MHz
Short wave radio	5.9 to 26.1 MHz
Citizen's band (CB) radio (40 channels)	26.96 to 27.41 MHz
Radio controlled airplanes	27.255 MHz (shared with CB channel 23)
Broadcast television channels 2-6	54 to 88 MHz
FM radio	88 to 108 MHz
Broadcast television, channels 7-13	174 to 220 MHz
Garage door openers, alarms	~40 MHz
Cordless analog phones	40-50 MHz
Baby monitors	49 MHz
Radio controlled airplanes	~72 MHz
Radio controlled cars	~75 MHz
Remote keyless entry (RKE) systems, tire pressure monitoring systems (TPMS)	315 or 433 MHz
UHF television (channels 14-83)	470 to 890 MHz

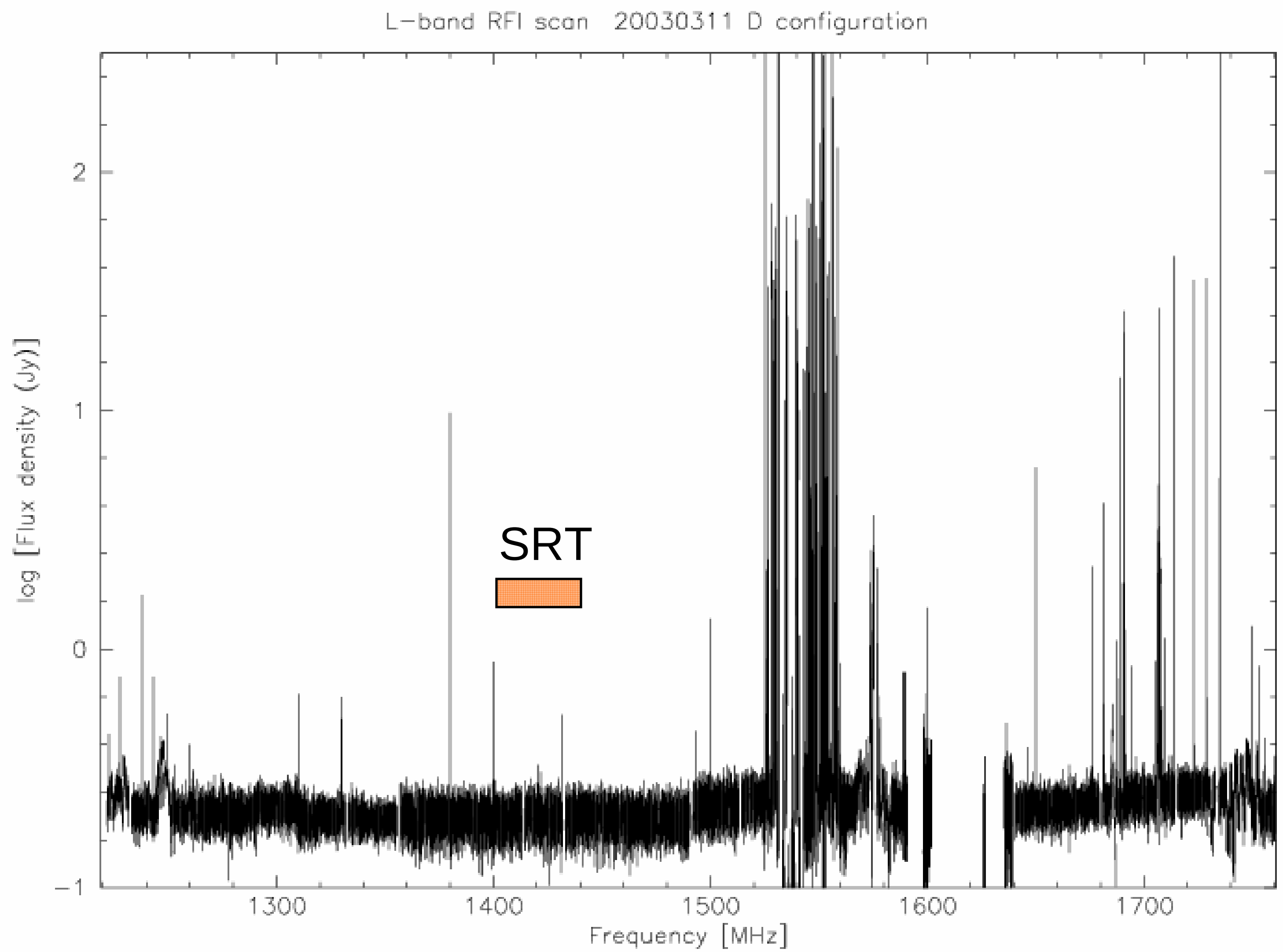
Radio Frequency Allocations

Wildlife tracking collars	215 to 220 MHz
Cordless phones	864 to 868 MHz 944 to 948 MHz
Cell phones (GSM)	824 to 960 MHz
Industrial, medical & scientific (ISM) band	902 to 928 MHz
Air traffic control radar	960 to 1215 MHz
Global positioning system GPS)	1227.6 MHz (L2 band, 20 MHz wide) 1575.42 MHz (L1 band, 20 MHz wide)
Globalstar satellite phone downlink Globalstar satellite phone uplink	1610.73 to 1625.49 MHz 2484.39 to 249.15 MHz
Cell phones (GSM)	1710 to 1990 MHz
Digital cordless phones	1880 to 1900 MHz
Personal handy phone system (PHS)	1895 to 1918 MHz
Deep space radio communications:	2290 to 2300 MHz
Industrial, medical & scientific (ISM) band	2400 to 2483.5 MHz
Shared wireless data protocols (Bluetooth, 802.11b):	2402 to 2495 MHz
Microwave ovens	2450 MHz

Radio Frequency Allocations

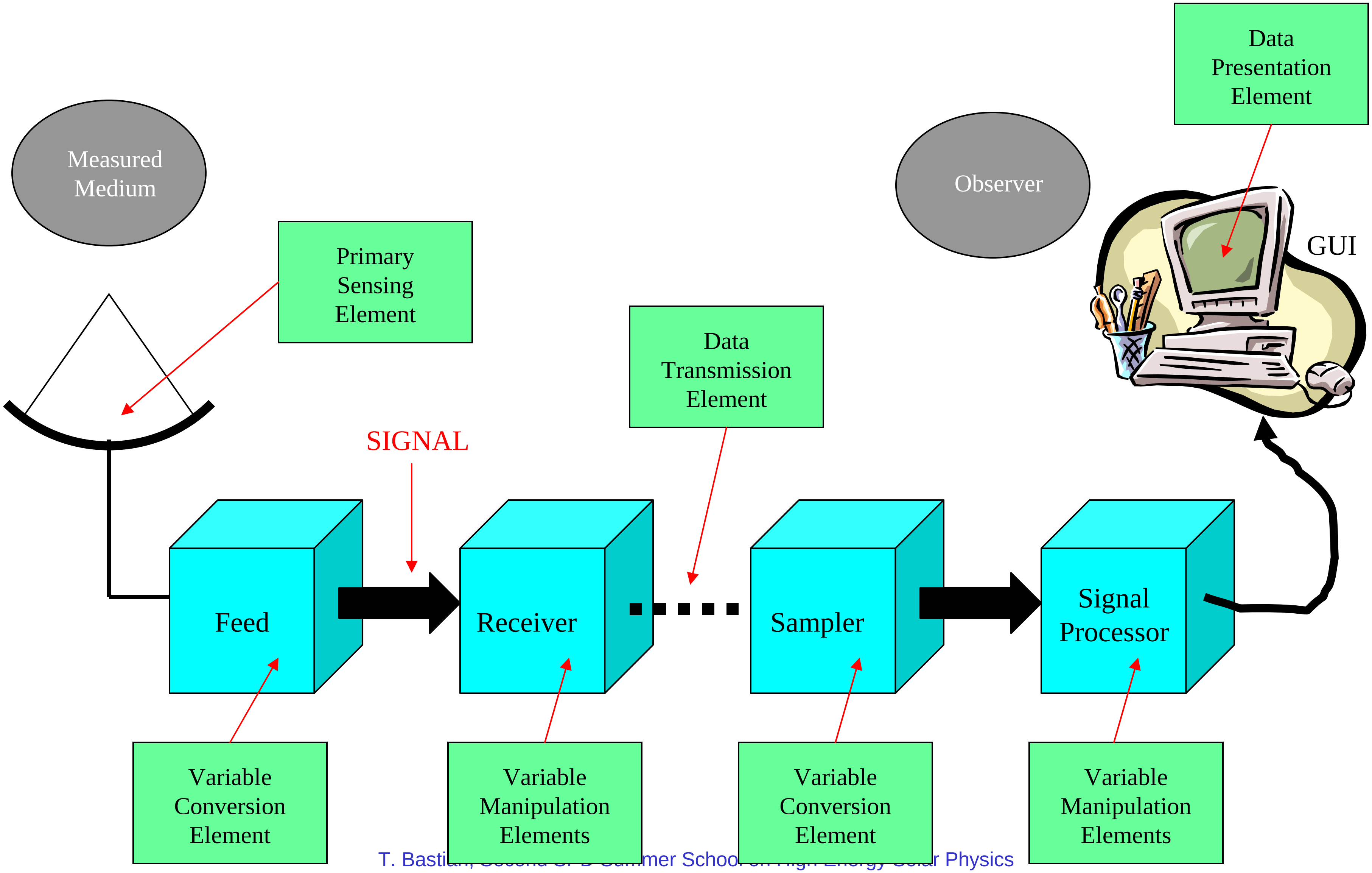
Satellite radio downlink XM Satellite Sirius Satellite	2330 to 2345 MHz 2332.50 to 2,345.00 MHz 2320.00 to 2,332.50 MHz
Radio altimeters	4.2 to 4.4 GHz
802.11a wireless local area network (WLAN)	5.15 to 5.25 GHz (lower band) 5.25 to 5.35 GHz (middle band) 5.725 to 5.825 (upper band)
Industrial, medical & scientific (ISM) band	5.725 to 5.85 GHz
Satellite radio uplink	7.050 to 7.075 GHz
Police radar	10.525 GHz (X-band) 24.150 (K-band) 33.4 to 36 GHz (Ka-band)
Direct broadcast satellite TV downlink (Europe)	11.7 to 12.5 GHz
Direct broadcast satellite TV downlink (US) for example, Echostar's Dish Network	12.2 to 12.7 GHz
Automotive radar, distance sensors	24 GHz
4G (fourth generation wireless)	59 to 64 GHz (U.S. general wireless) 59 to 62 GHz (Europe, WLAN) 62 to 63 GHz (Europe, mobile broadband) 65 to 66 GHz (Europe, mobile broadband)
Automotive radar, adaptive cruise control	76 to 77 GHz
E-band (new FCC-approved ultra-high speed data communications band)	76 GHz, 81 to 86 GHz and 92 to 95 GHz

Radio Frequency Interference



Antennas and Arrays

Radio Telescope Functional Blocks



Purpose of the Antenna

1. Collect of a tiny bit of radiation for use in the measurement process.

   Collecting Area

2. Spatial filtering

   Directionality or Pointing

3. Convert EM flux density to an electrical signal

   Feed Point to extract the collected energy – energy conversion process

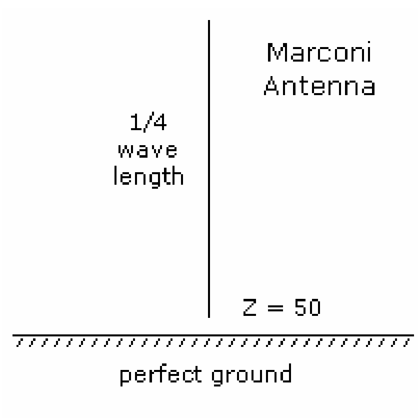
4. Spectral Filtering

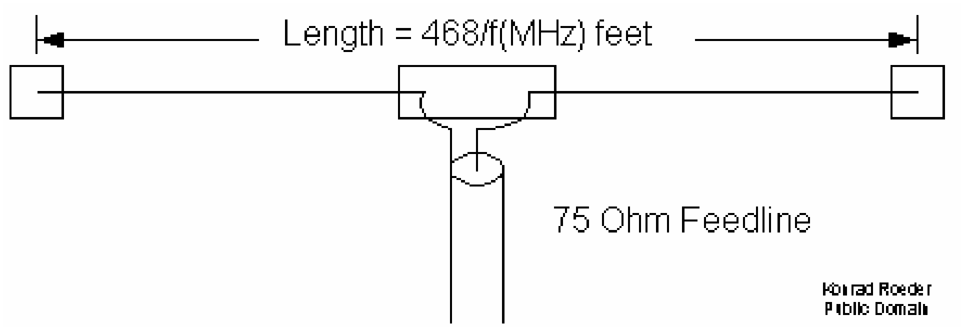
   Will operate over a specific range or "spectral band" of radiation

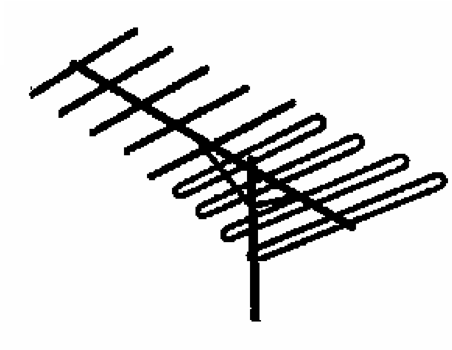
Antennas and Arrays

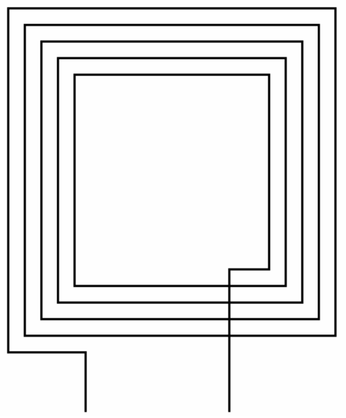
Antennas are structures designed to collect or transmit radio waves.

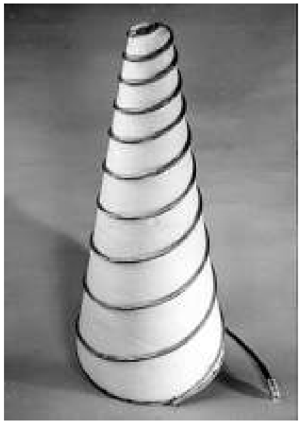
Antenna designs constitute a nearly uncountable set…





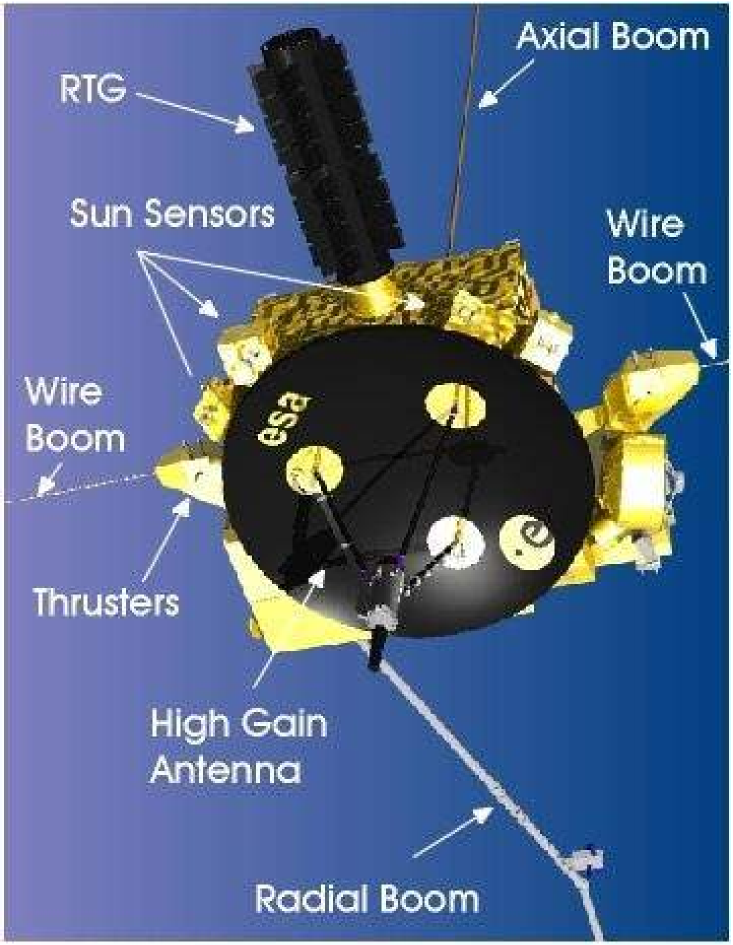




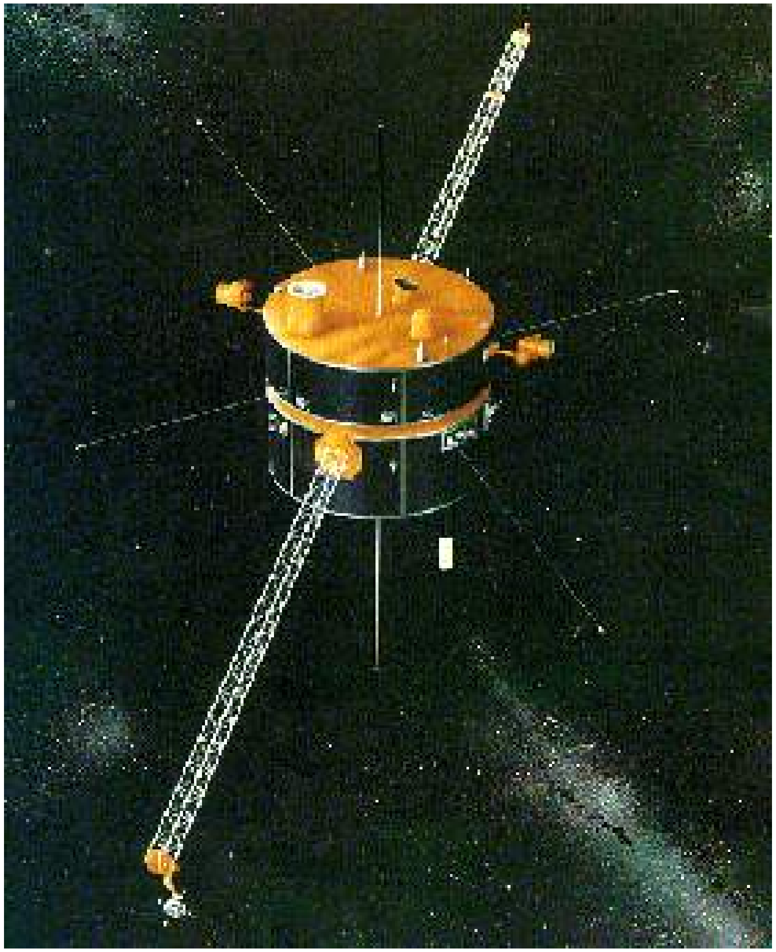


Antennas and Arrays

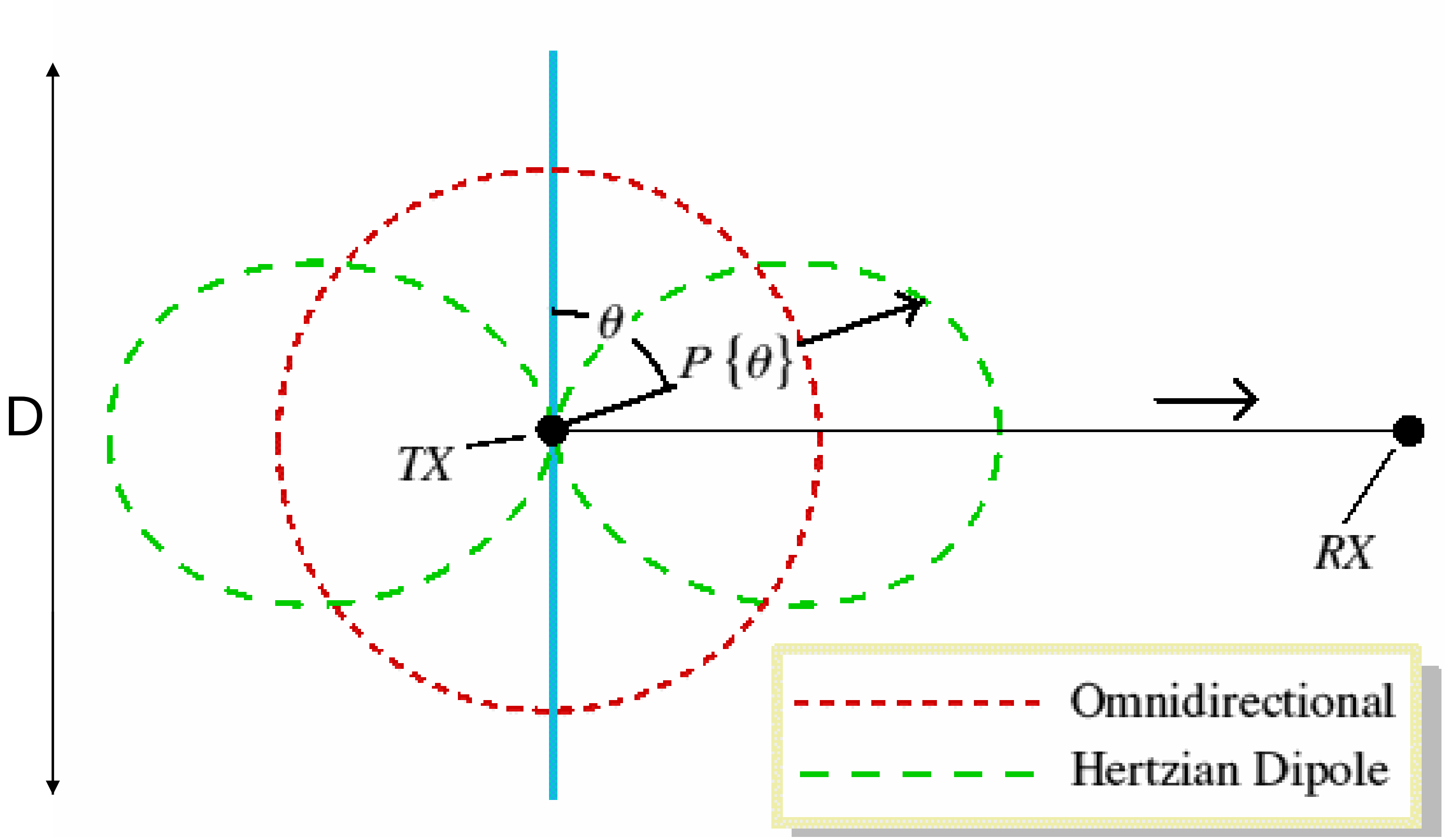
Ulysses/URAP



WIND/WAVES



Simplest case: Hertzian dipole (D<<λ)



Antennas and Arrays

The design of a particular antenna must be matched to the problem at hand. Low frequency antennas (ν < few x 100 MHz) may employ some variant of a dipole or phased dipole array since their effective area is proportional to λ^2.

At higher frequencies, signal is collected with a mirror that most often takes the form of a parabolic reflector of diameter $D \gg \lambda$. This focuses radiation on a feed that couples the radiation to electronics that amplify the signal.

For our purposes, we will consider a conventional parabolic antenna in order to illustrate some basic concepts before discussing interferometry and Fourier synthesis imaging (which is basically what RHESSI does).

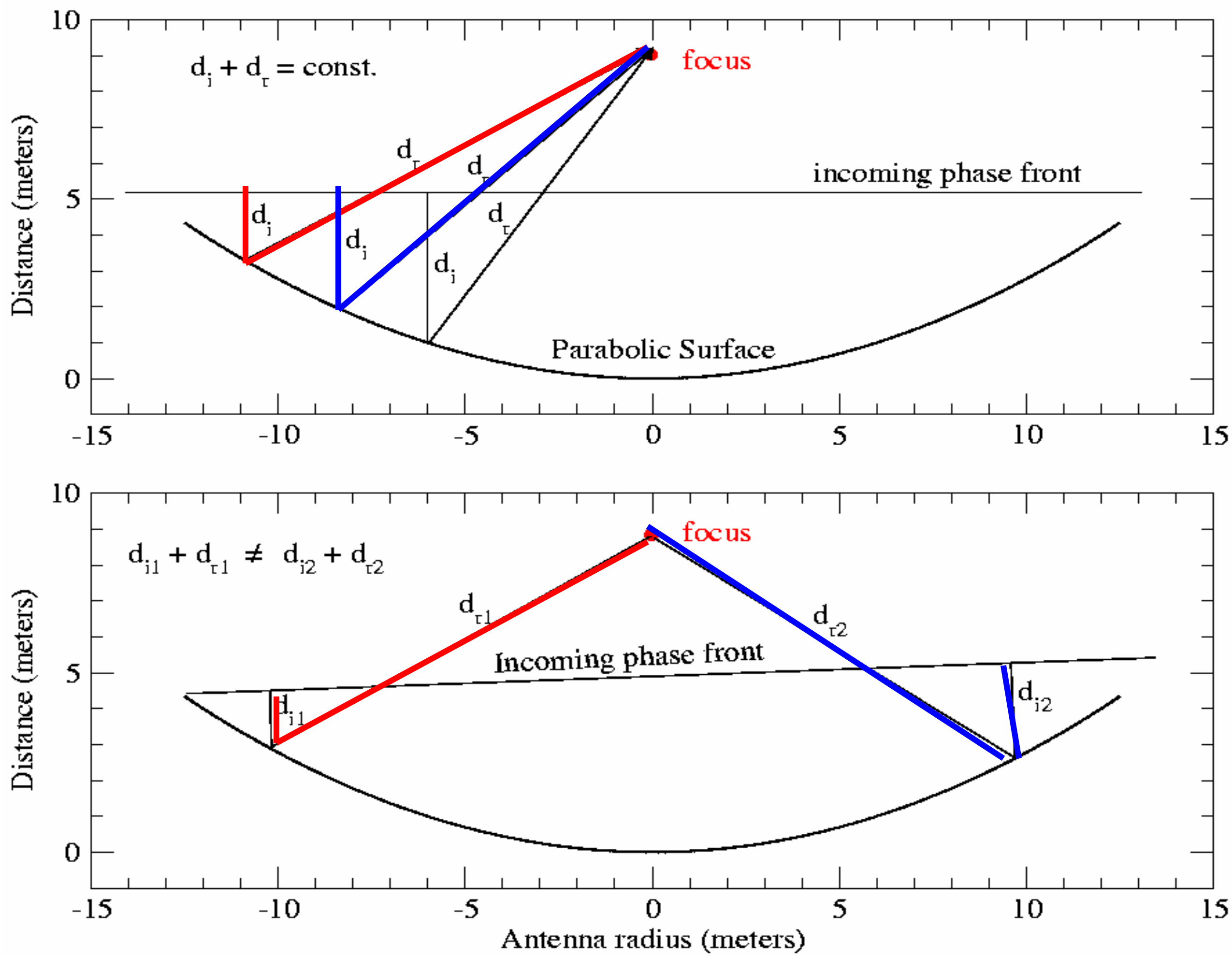
Antennas and Arrays

Let's use a parabolic single dish to illustrate some basic points.

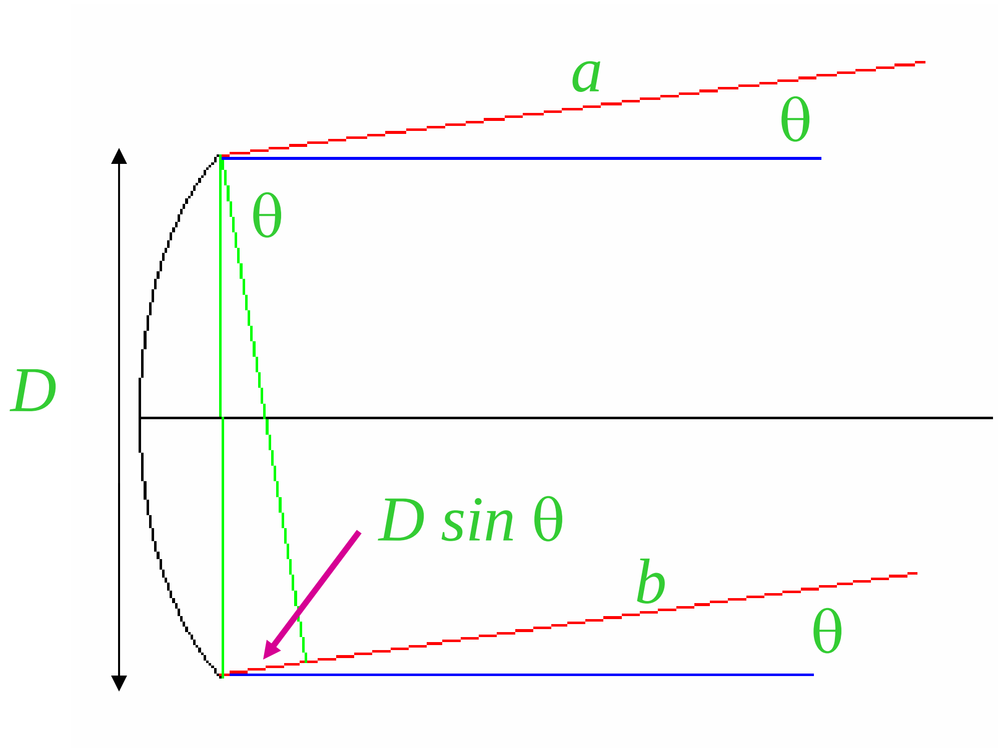
Resolution

Antenna response function

Antenna gain



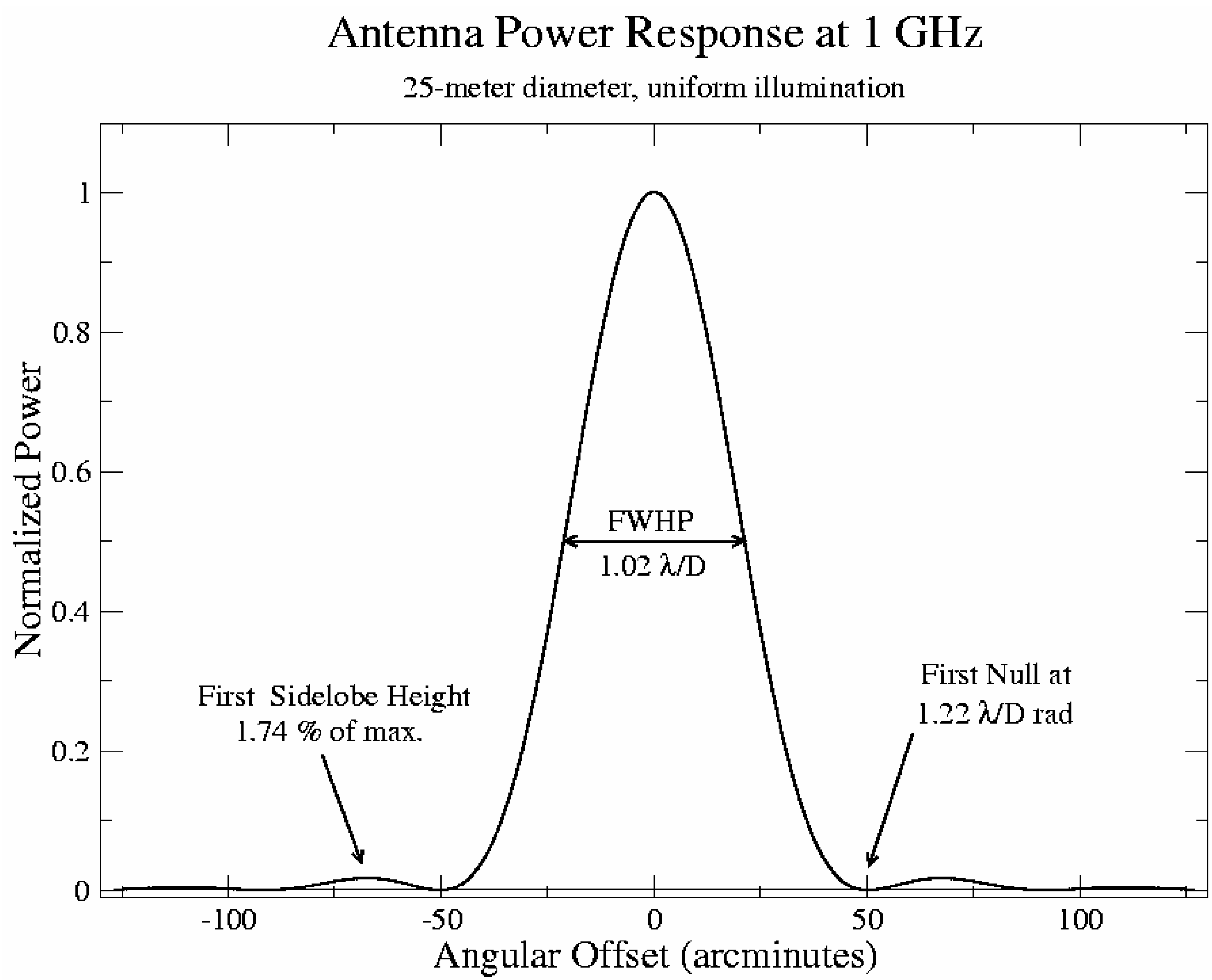
Antennas and Arrays



$$\frac{D\theta}{\lambda} = 1 \quad \rightarrow \quad \theta = \frac{\lambda}{D}$$

Ray b travels a distance $D \sin \theta$ farther than ray a. The two rays therefore arrive at the focus with a phase difference of $\Delta\phi = D \sin \theta/\lambda$ wavelengths, or $D\theta/\lambda$ when θ is small. When this difference is plus or minus $\lambda/2$, the two rays are completely out of phase and their contributions cancel. The angle θ at which this happens characterizes the angular resolution of the aperture.

The Standard Parabolic Antenna Response



Antennas and Arrays

Effective collecting area

$A_{eff}(\nu,\theta,\phi)$ m^2

On-axis response:

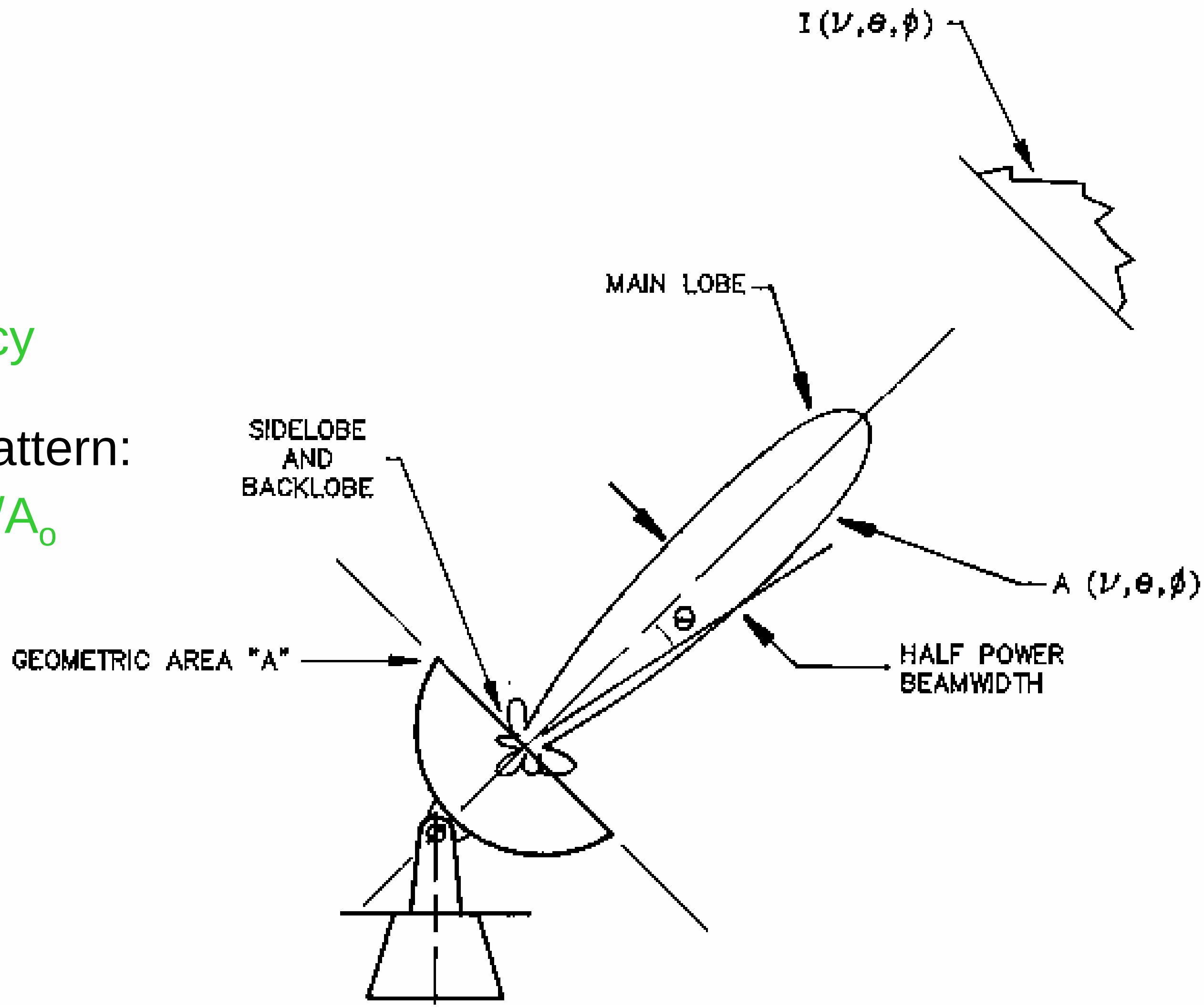
$A_o = \eta A$

A = physical area

η = antenna efficiency

Normalized antenna pattern:

$P_n(\nu,\theta,\phi) = A_{eff}(\nu,\theta,\phi)/A_o$



Antennas and Arrays

The beam solid angle at frequency ν is then given by

$$\Omega_A = \iint_{4\pi} P_n(\nu, \theta, \phi) d\Omega$$

The antenna gain is given as the ratio of the beam solid angle to that of an isotropic antenna (or 4π):

$$G = \frac{4\pi}{\Omega_A}$$

Sometimes measured as a ratio to an idealized isotropic antenna in dBi.

Using the fundamental relation that $\lambda^2 = A_o \Omega_A$,

$$G = \frac{4\pi}{\lambda^2} A_o$$

Hertzian (short) dipole:

G = 1.5 = 1.76 dBi

VLA antenna (20 cm):

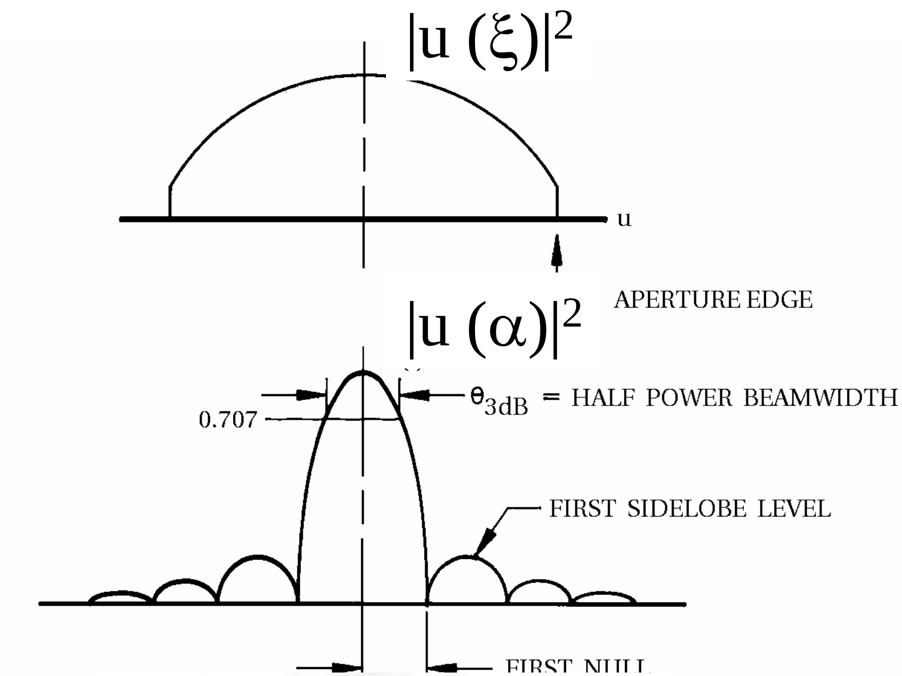
G = 1.3×10^5 = 51 dBi

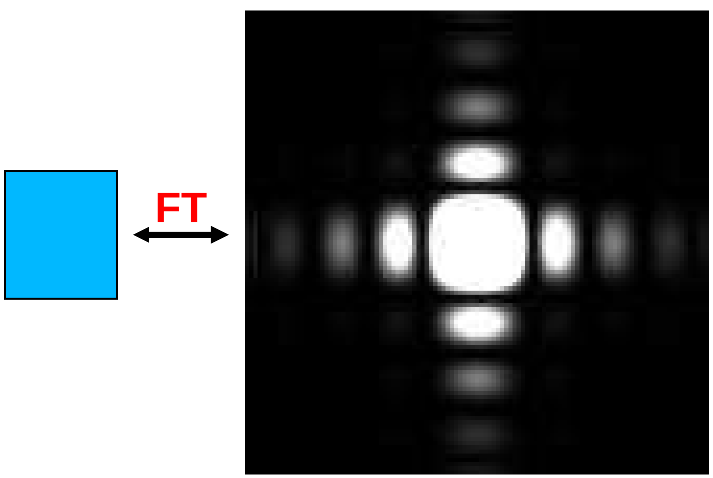
Aperture-Beam Fourier Transform Relationship

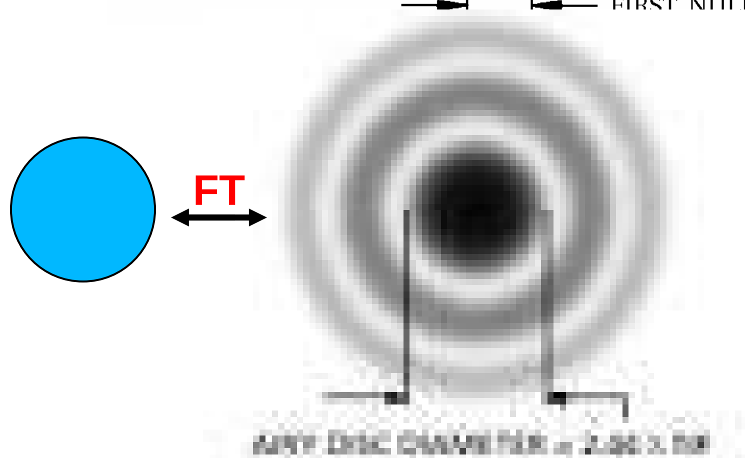
u (ξ, η) = aperture illumination
= Electric field distribution across the aperture
(ξ, η) = aperture coordinates

FT

u(α,β) = far-field electric field
(α , β) = direction relative to "optical axis" of telescope







Antennas and Arrays

The solid angle of the main lobe of the antenna power pattern is

$$\Omega_M = \iint_{main\ lobe} P_n(\theta,\phi)\,d\Omega$$

Now the flux density from a source on the sky with a brightness distribution (specific intensity) $B(\theta,\phi)$ erg cm^{-2} s^{-1} Hz^{-1} ster^{-1} is

$$S_\nu = \iint_{source} B(\theta,\phi)\,d\Omega$$

If the normalized power pattern of an antenna is $P_n(\theta,\phi)$ the flux density within the telescope beam is

$$S_\nu = \iint_{4\pi} B(\theta,\phi)P_n(\theta,\phi)\,d\Omega$$

Antennas and Arrays

If the angular size of the source is very small compared to the main lobe of the beam, $P_n = 1$ over the source and the measured flux density is the true flux density.

If the source has an angular extent greater than the main beam, the measured flux density must be less than the true value. For an extended source of constant brightness

$$S_\nu = B_o \iint_{4\pi} P_n(\theta,\phi)\,d\Omega \approx B_o \Omega_M$$

Note that $B_o = S_\nu/\Omega_M$ – flux density per beam is thus a measure of the brightness or the specific intensity!

One needs a small beam size – a large dish - to make meaningful measurements of the specific intensity in an extended source.

Units

Source flux: $W\ m^{-2}$ or $ergs\ cm^{-2}\ s^{-1}$

Flux density: $W\ m^{-2}\ Hz^{-1}$ or $ergs\ cm^{-2}\ s^{-1}\ Hz^{-1}$

1 Jansky = $10^{-26}\ W\ m^{-2}\ Hz^{-1}$

1 solar flux unit = 10^4 Jy

Specific intensity: $W\ m^{-2}\ Hz^{-1}\ ster^{-1}$ or

$ergs\ cm^{-2}\ s^{-1}\ Hz^{-1}\ ster^{-1}$

Jy/beam

SFU/beam

Brightness Temperature (K)

Brightness Temperature

Thermal radiation is radiation emitted by matter in thermal equilibrium; i.e., material that can be characterized by a macroscopic temperature T. Material in thermal equilibrium that is optically thick is referred to as a black body.

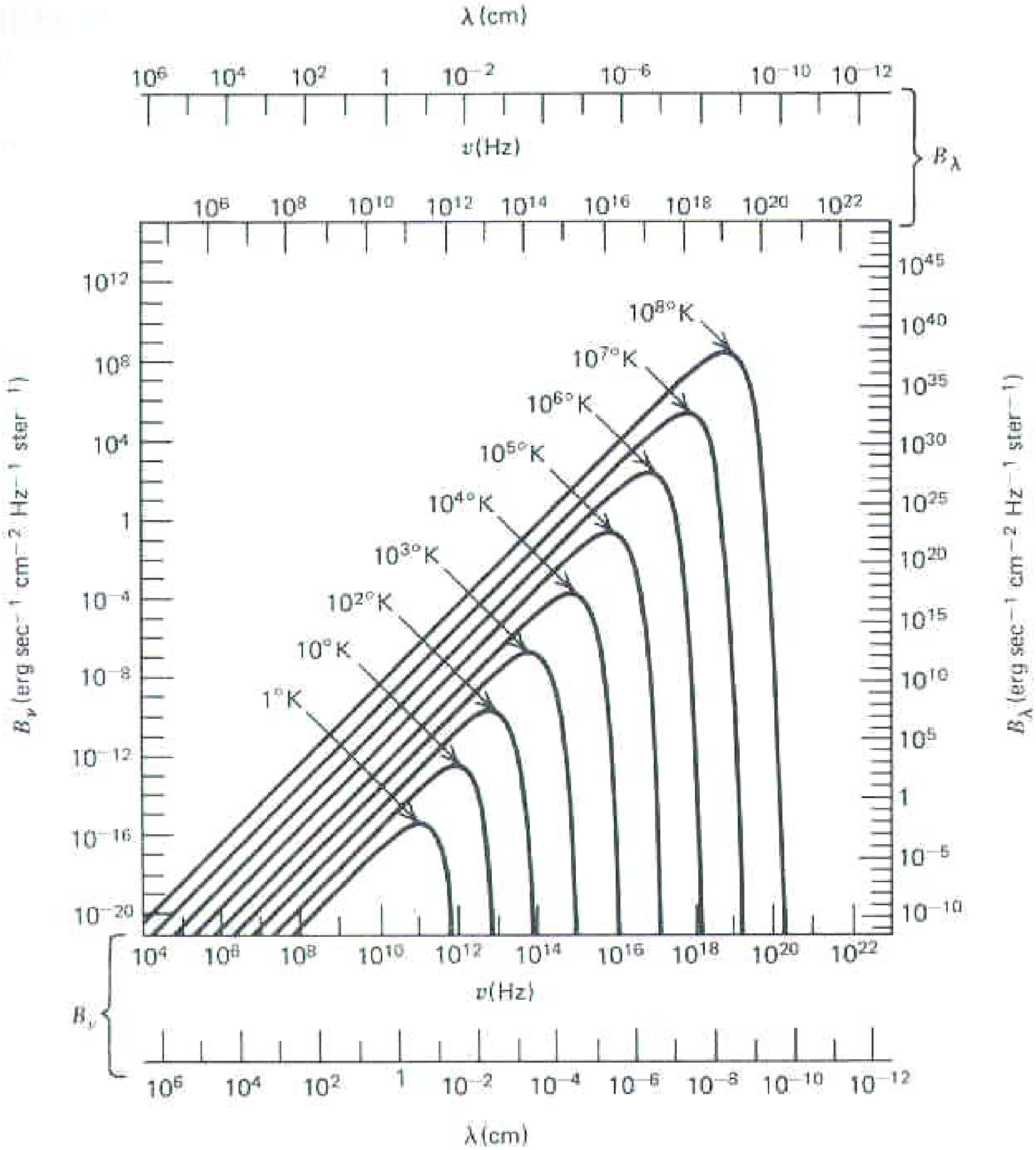
The specific intensity of a black body is described by the Planck function:

$$I_\nu(T) = B_\nu(T) = \frac{2h\nu^3}{c^2}\frac{1}{e^{h\nu/kT}-1}$$

Which is itself characterized by the temperature of the body, T.

Brightness Temperature

Planck function



Brightness Temperature

Note that when

$$h\nu / kT << 1 \;\rightarrow\; e^{h\nu/kT} - 1 \approx 1 + \frac{h\nu}{kT} - 1 = \frac{h\nu}{kT}$$

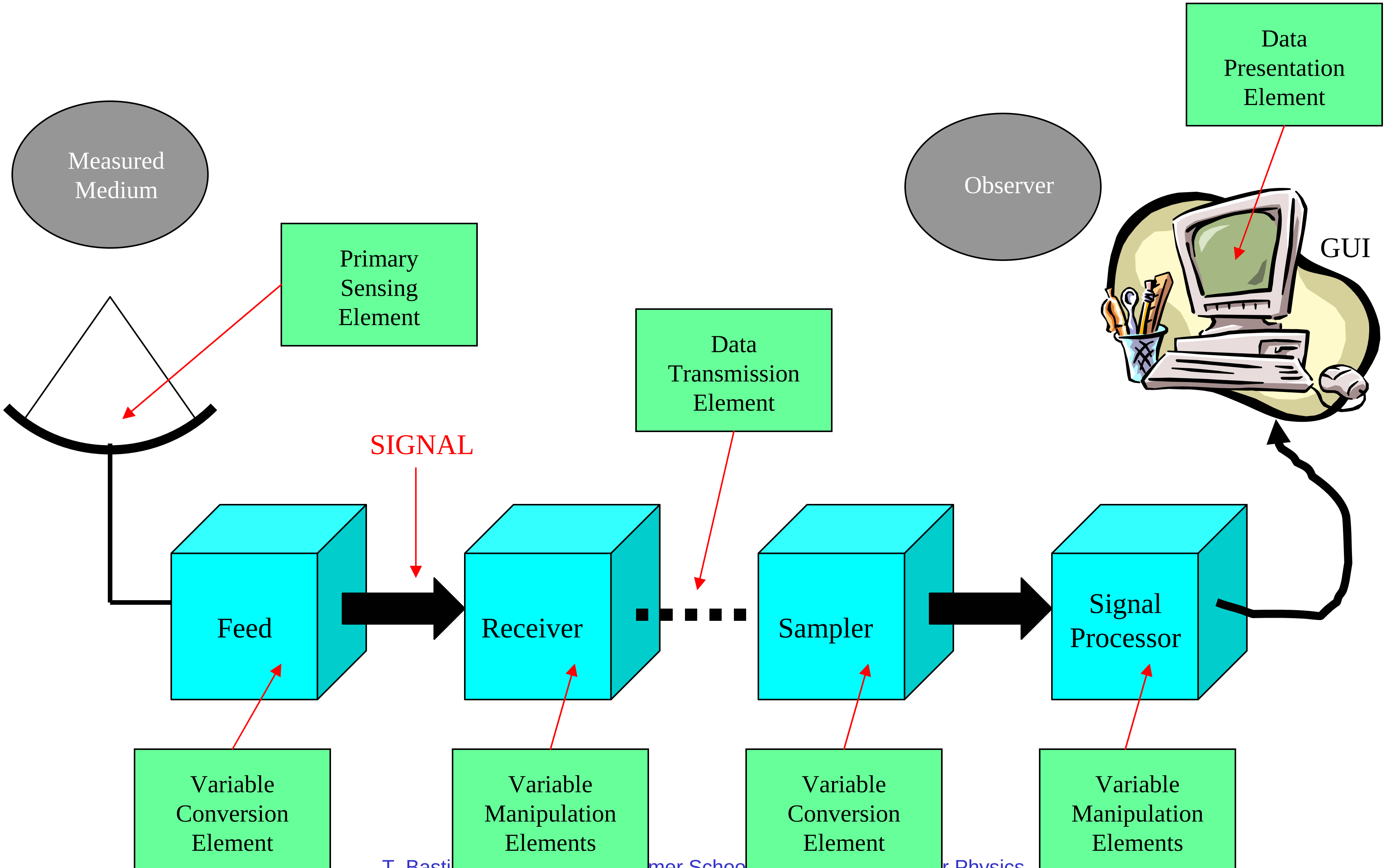
it simplifies to the Rayleigh-Jeans Law.

$$B_\nu(T) = \frac{2h\nu^3}{c^2}\frac{1}{e^{h\nu/kT} - 1} \approx \frac{2\nu^2}{c^2}kT$$

It is useful to now introduce the concept of brightness temperature T_B, which is defined by

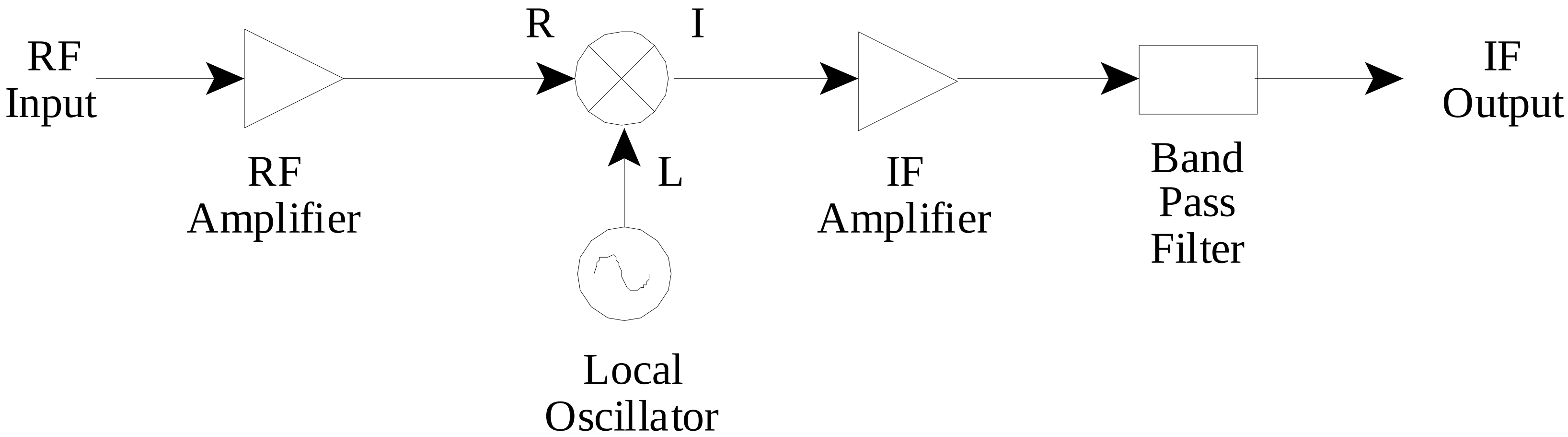
$$I_\nu = B_\nu(T_B) = \frac{2\nu^2}{c^2}kT_B$$

Radio Telescope Functional Blocks

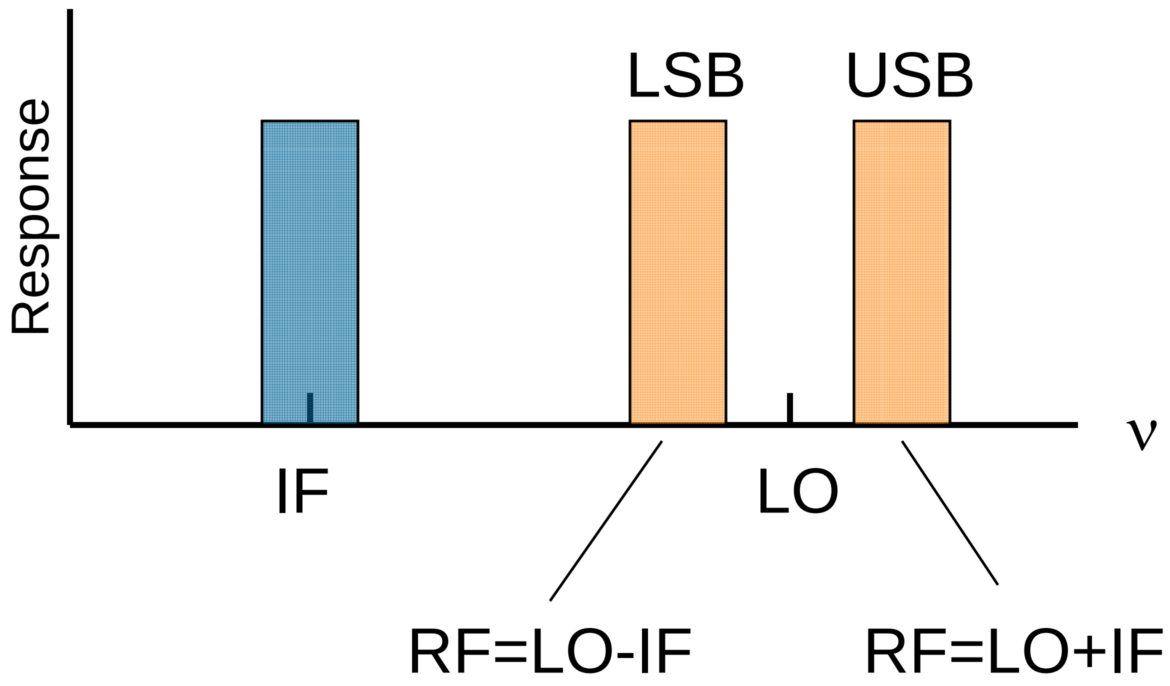


Heterodyne Detection

In its most basic form, the heterodyne receiver consists of a radio frequency (RF) section, which performs signal processing functions such as amplification and spectral filtering in the frequency band of the incoming waves (the RF band), and an intermediate frequency (IF) section which performs additional processing functions but usually at a much lower frequency (the IF band).



RF to IF



A Few Performance Parameters

Noise – the uncertainty in the output signal. Ideally, this noise consists of only statistical fluctuations.

Linearity – the degree of which the output signal is proportional to the input photons that are collected.

Dynamic range – the maximum variation in the radiation power over which the detector output represents the photon flux.

Number and size of pixels – the number of picture elements that the detector can record simultaneously and the physical size of each element in the detector.

Time response – the minimum interval of time over which the detector can distinguish changes in the photon arrival rate.

Spectral response – the total wavelength or frequency range over which the photons can be detected with reasonable efficiency.

System and Antenna Temperature

The power output from a receiver can be expressed in terms of an equivalent temperature:

$$P_{out} = k_B T_{out} \Delta \nu$$

This can, in turn, be separated into various contributions due to the source, components of the system (feed, receiver, transmission lines, …) and other extraneous sources:

$$P_{out} = P_{src} + P_{sys} = k_B \Delta \nu (T_{ant} + T_{sys})$$

$$T_{sys} = T_{bg} + T_{sky} + T_{spill} + T_{loss} + T_{rx}$$

The contribution of a source S to T_{out} is referred to as the antenna temperature, with:

$$P_{src} = k_B T_{ant} \Delta \nu = S A_{eff} \Delta \nu / 2 \rightarrow T_{ant} = S A_{eff} / 2 k_B$$

Example

- A typical system temperature for a modern radio telescope is 30 K. What is the antenna temperature of a 1 Jy source observed by a 20 m antenna with an aperture efficiency of 0.6?

Ans: $$T_{ant} = SA_{eff} / 2k_B \approx 0.07K$$

- What if we point at the Sun and observe at a wavelength of 20 cm, for which the solar flux density ranges is ~100 SFU?

Ans: $$T_{ant} \approx 68000K$$

Solar Radio Observations

Some Examples

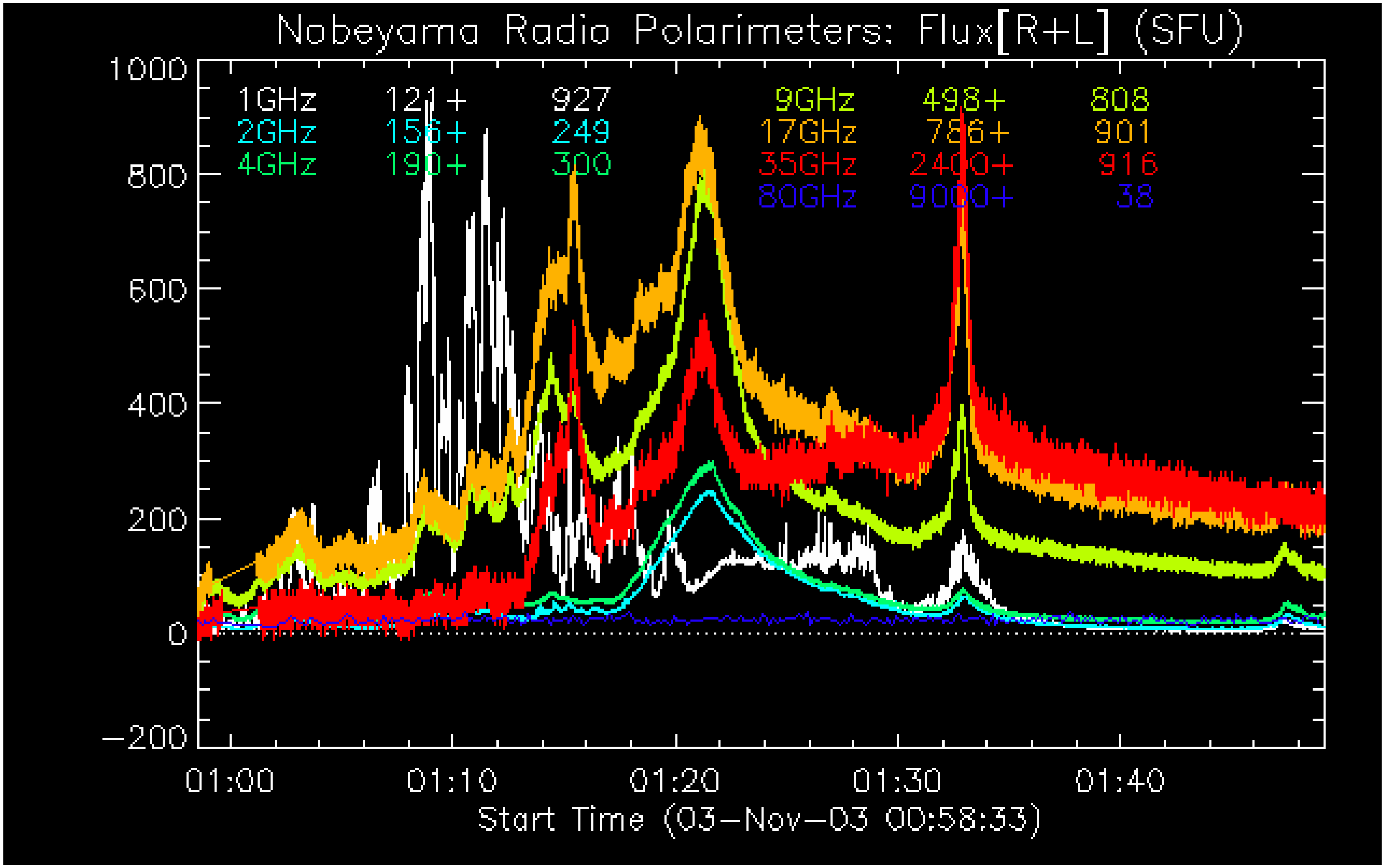
- Total flux monitoring
- Dynamic Spectroscopy

Solar Radio Observations

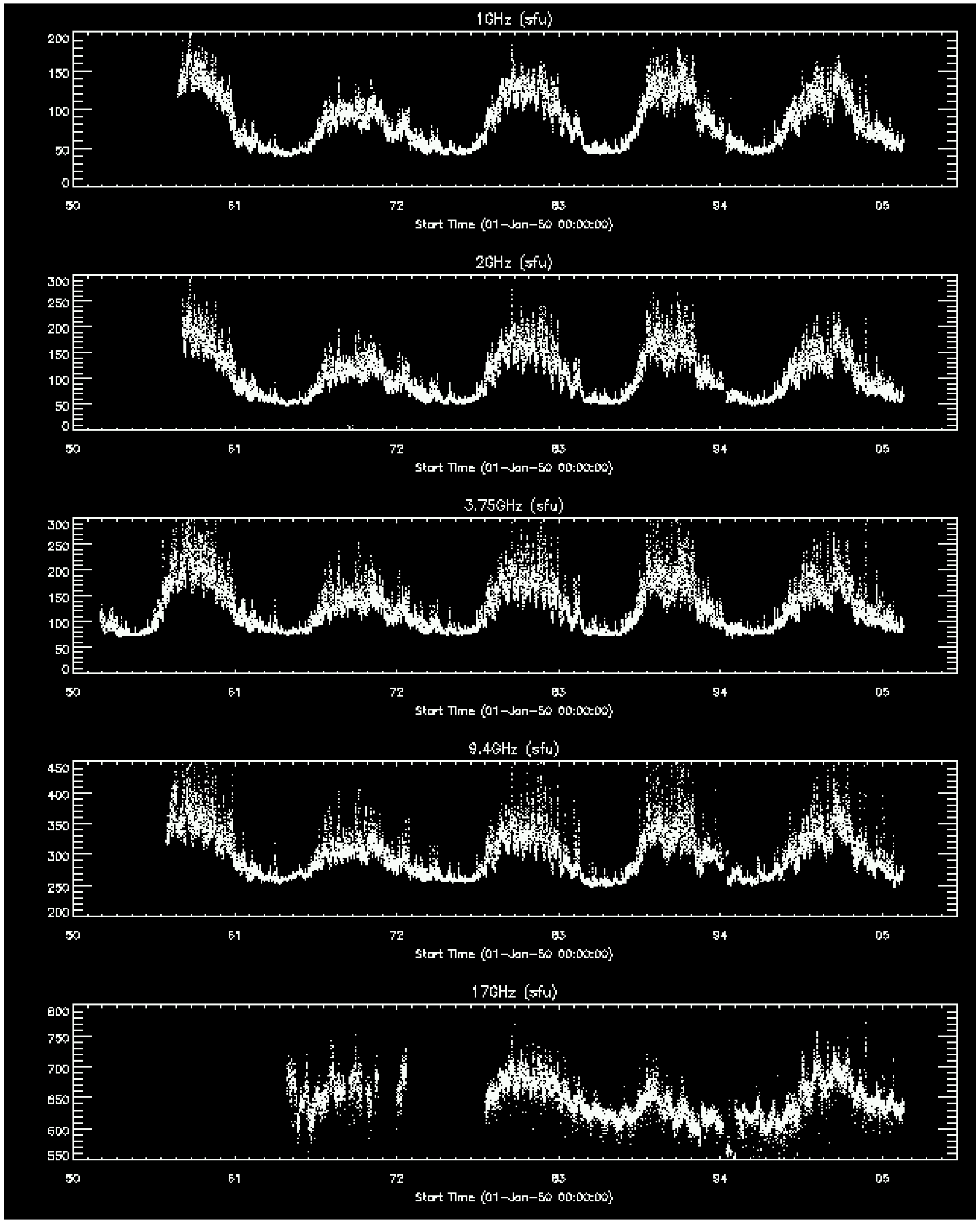
Nobeyama Polarimeters

(1,2,3.75, 9.4, 17, 35, and 80 GHz)

Solar Radio Observations



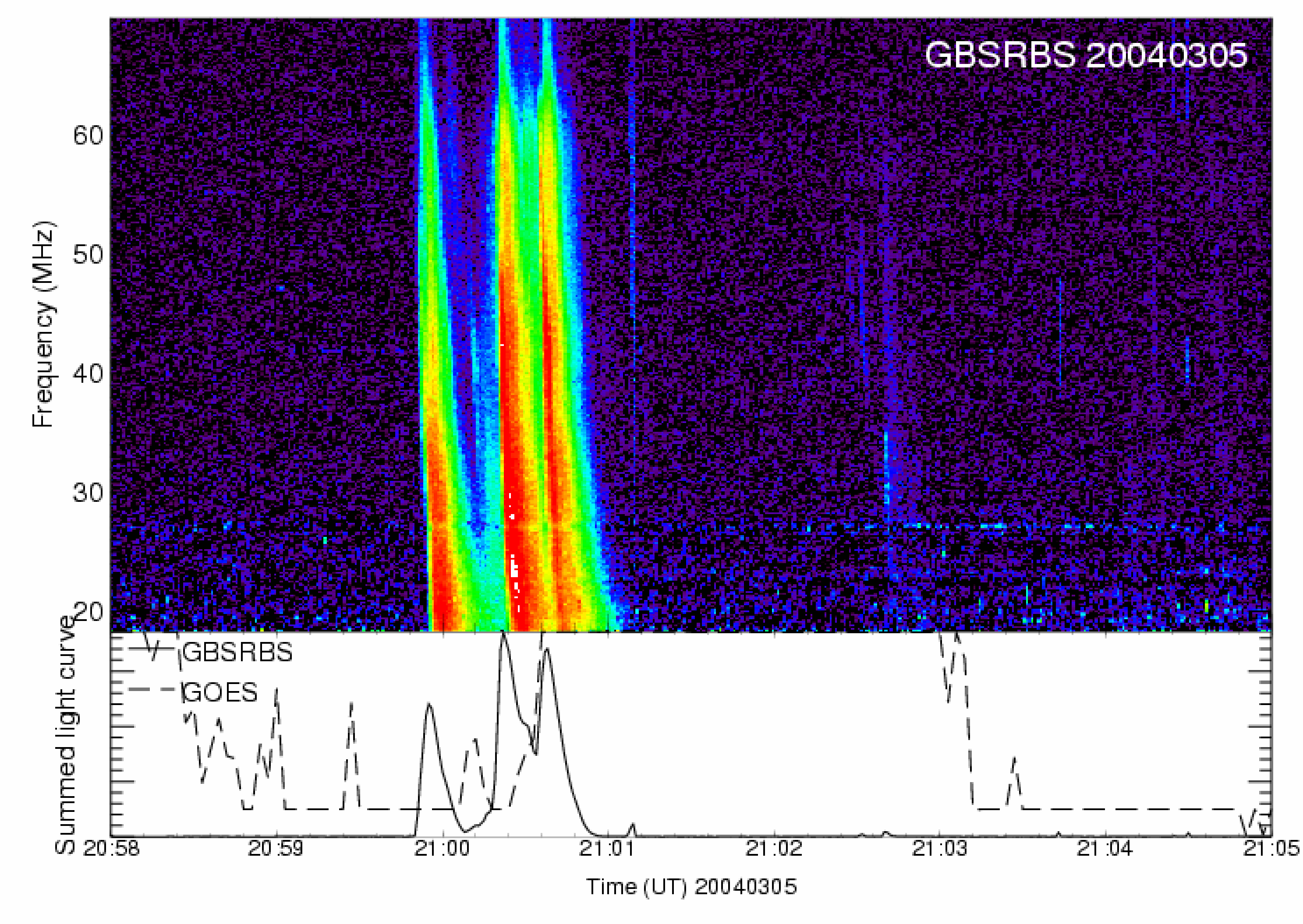
Solar Radio Observations



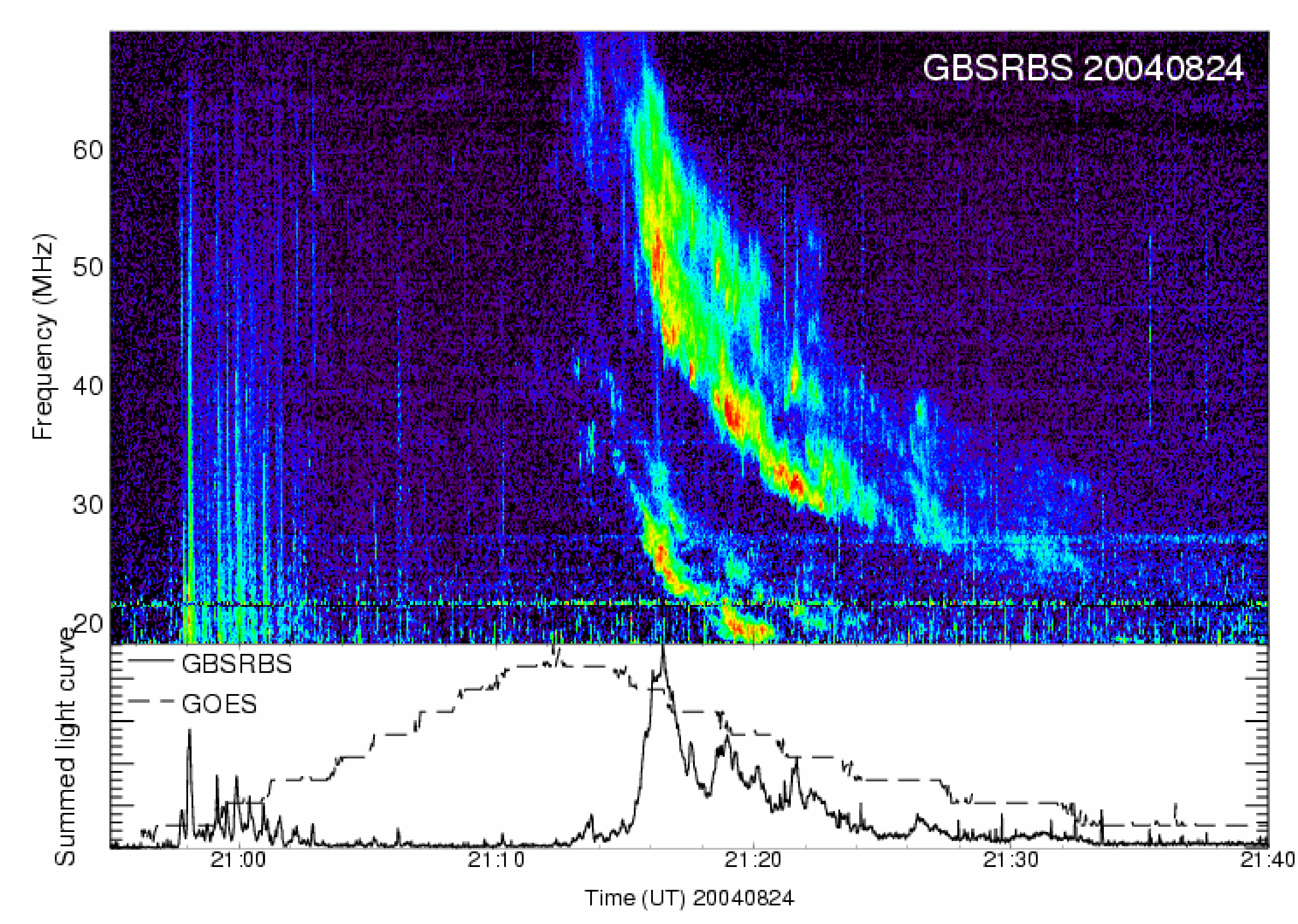
Solar Radio Observations

Green Bank Solar Radio Burst Spectrometer

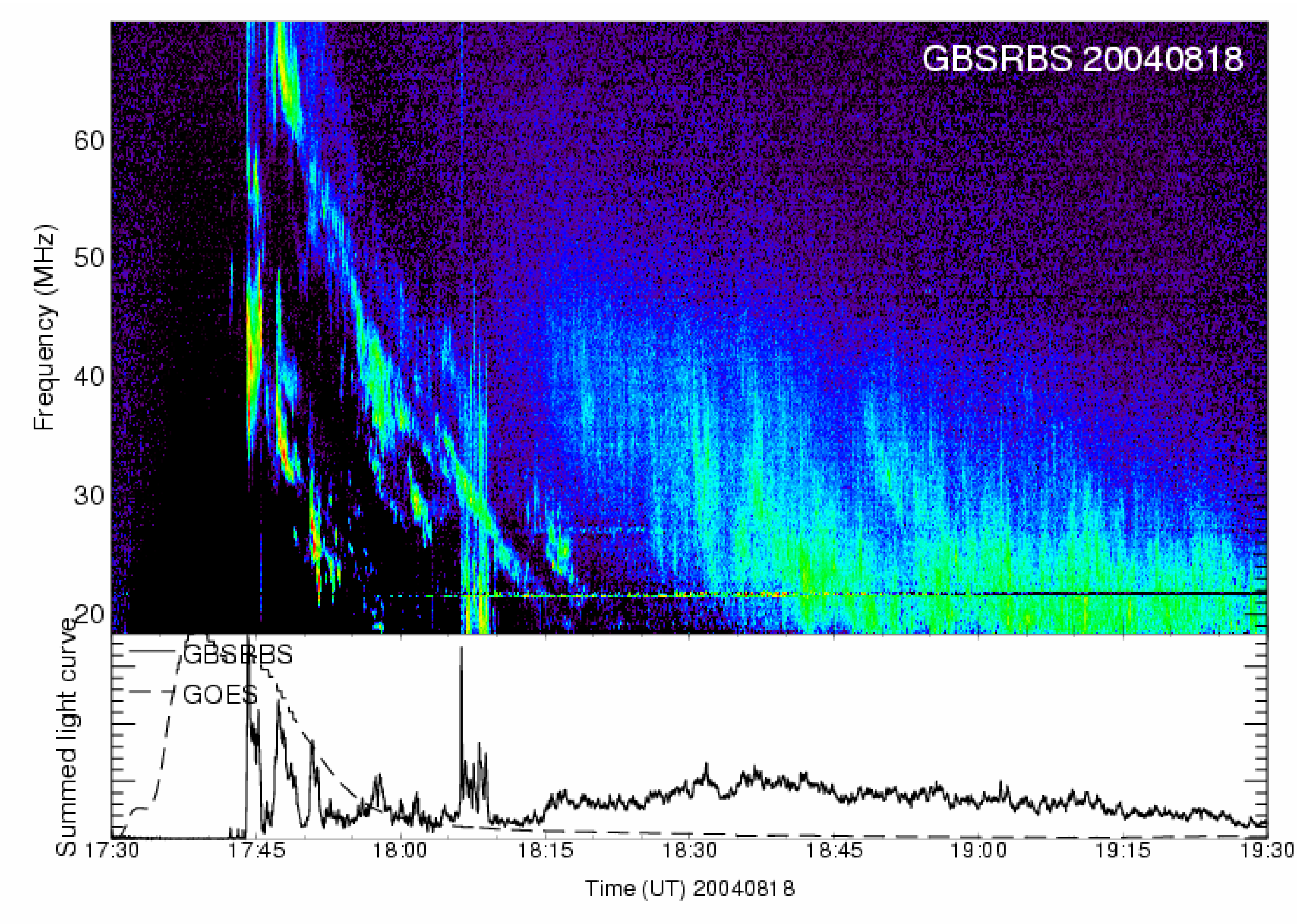
Solar Radio Observations



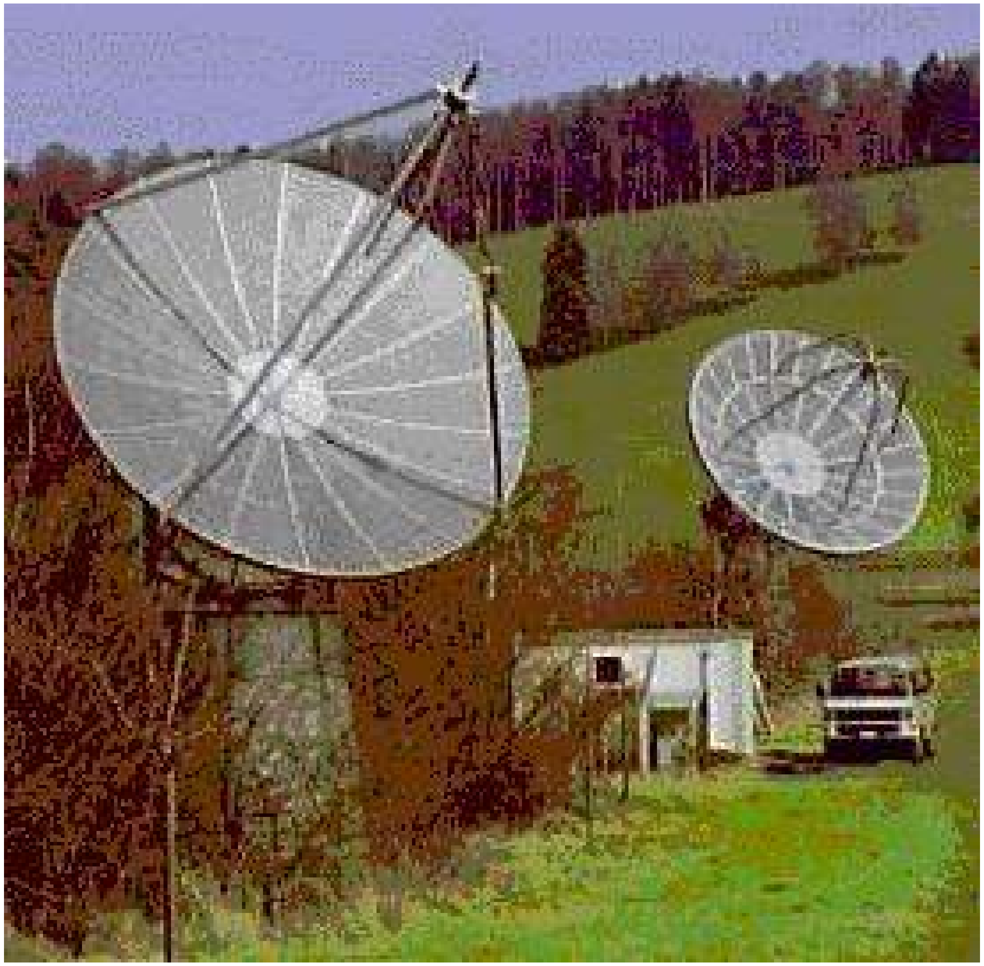
Solar Radio Observations



Solar Radio Observations

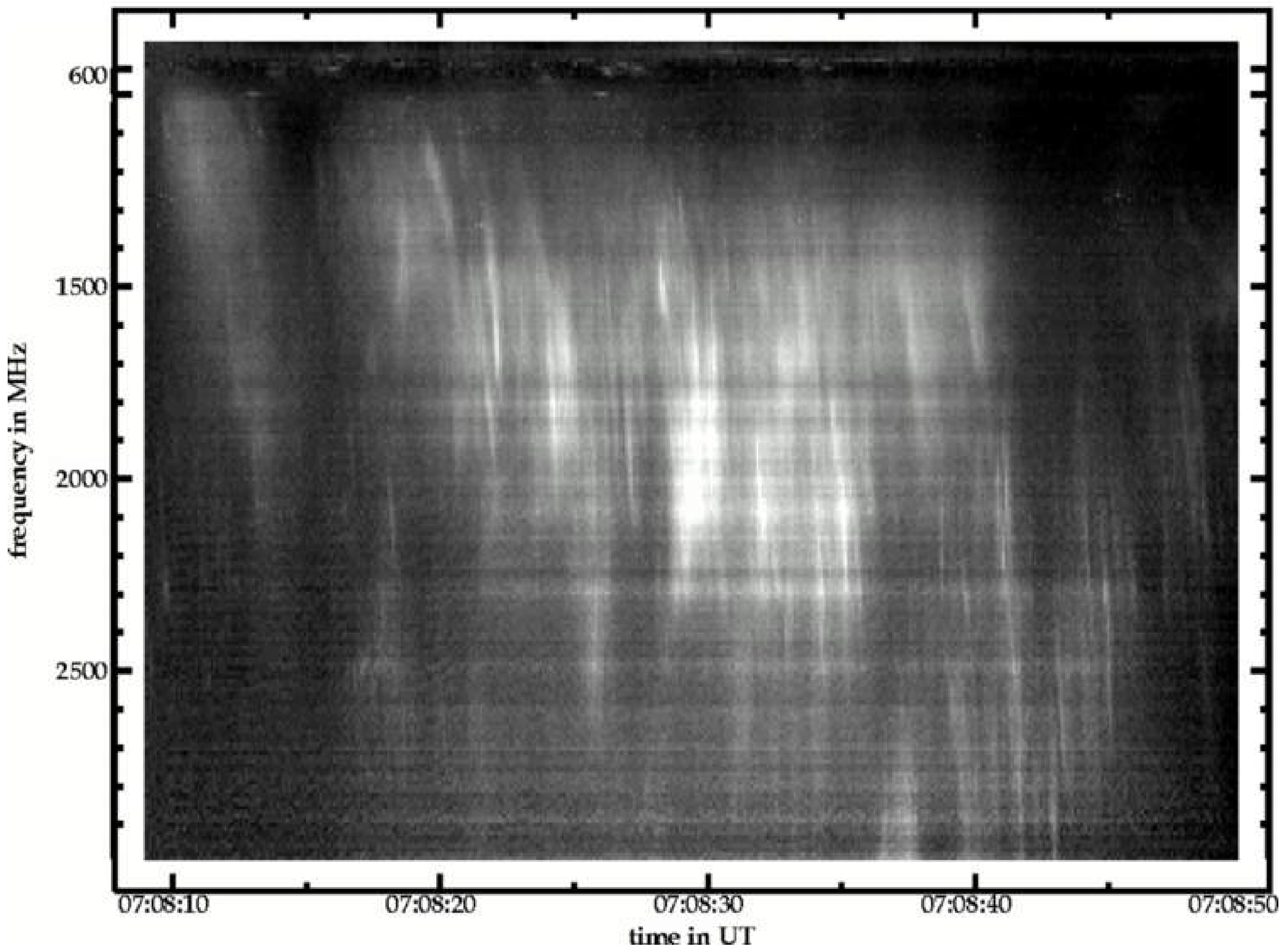


Solar Radio Observations



ETH instruments near
Bleien, Switzerland

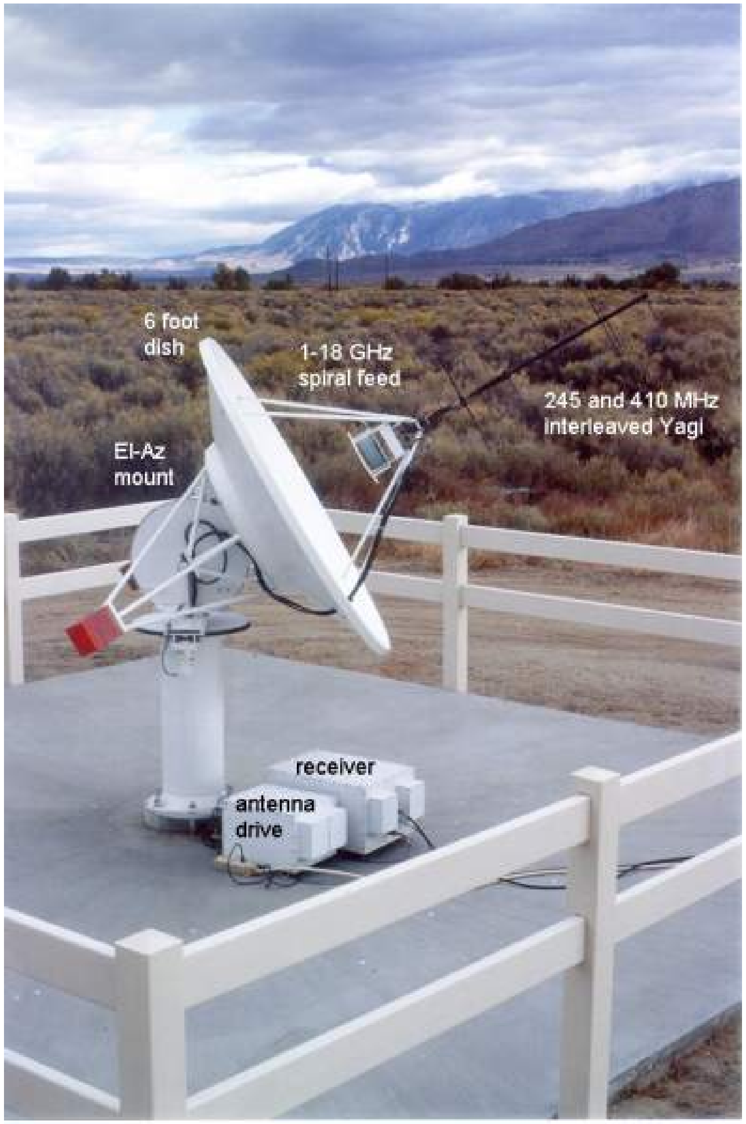
Solar Radio Observations



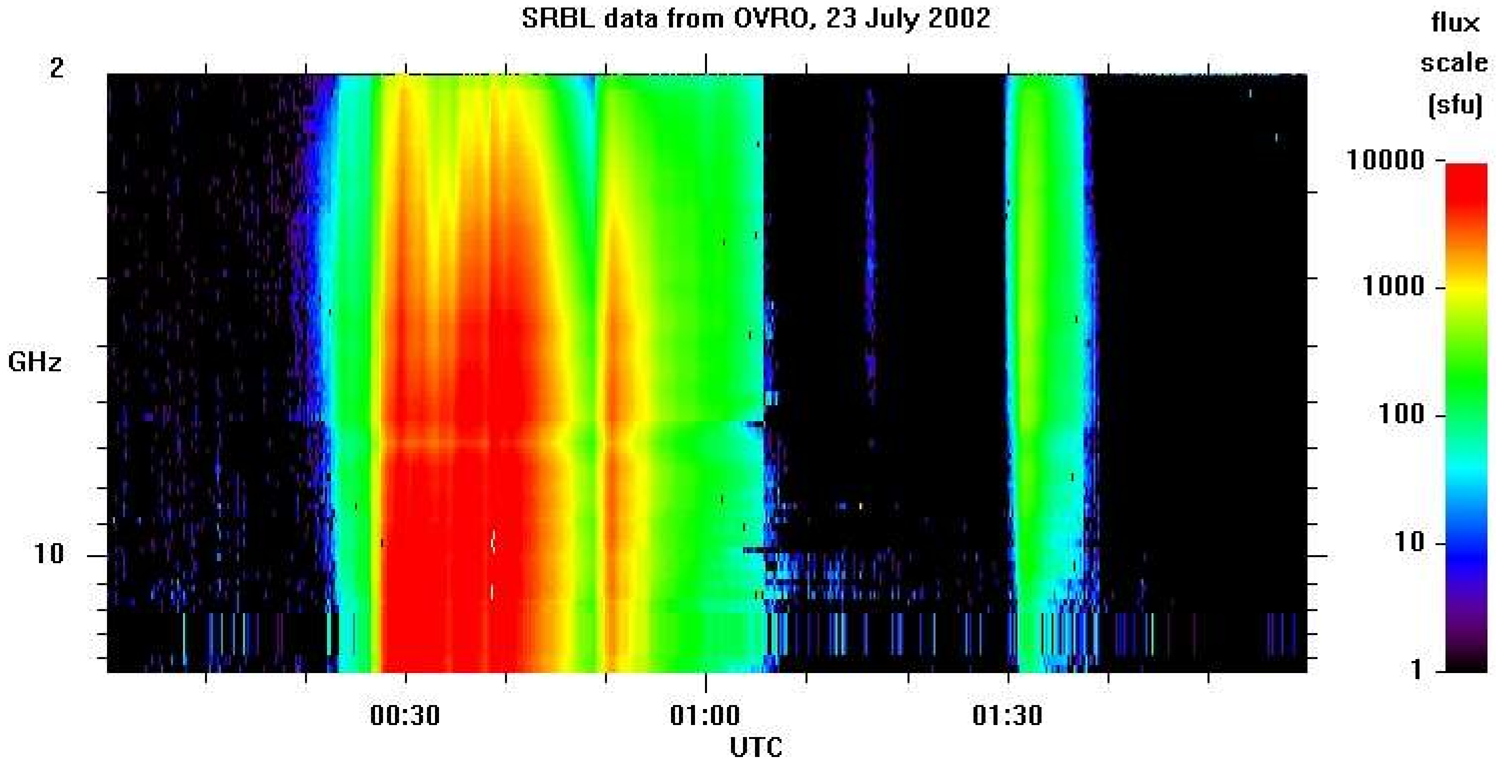
Solar Radio Observations

Solar Radio Burst Locator

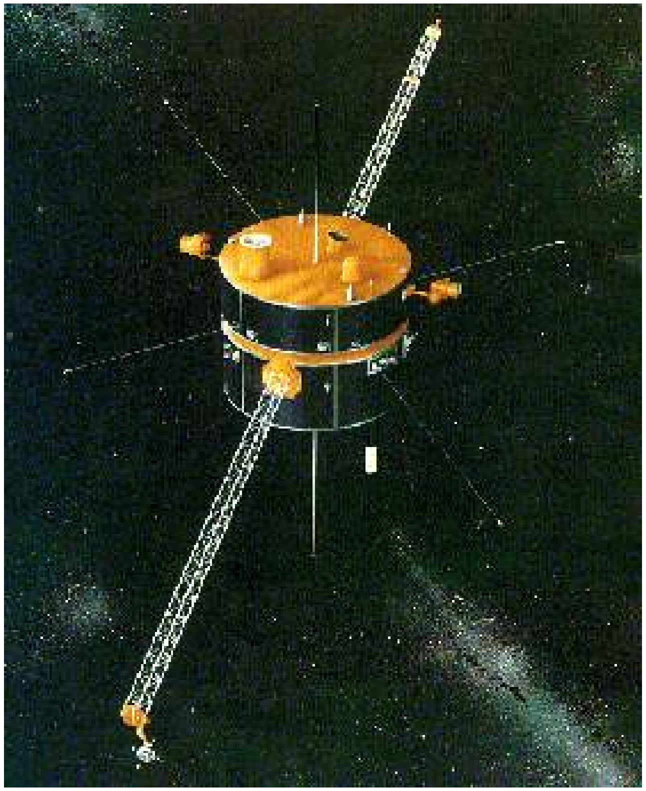
Owens Valley, CA

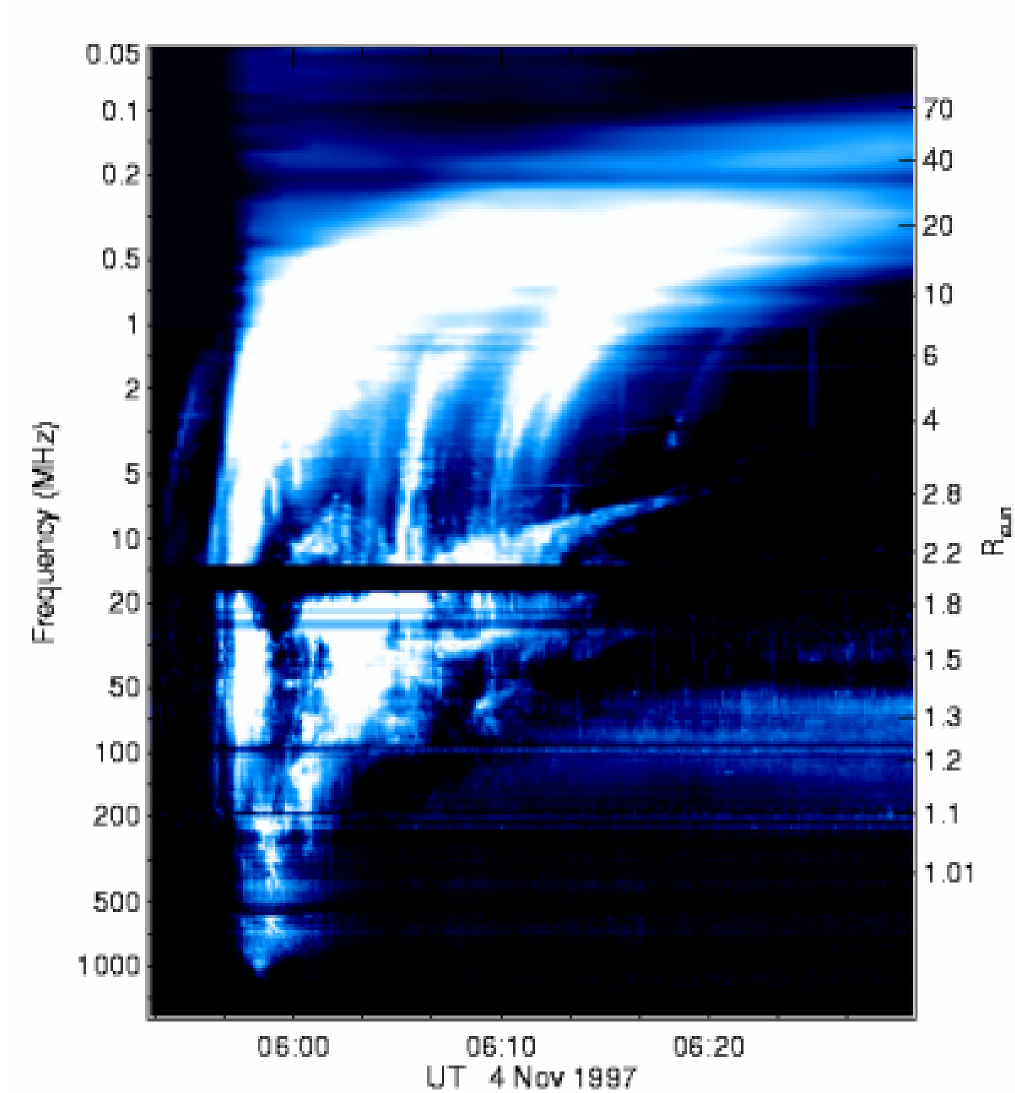


Solar Radio Observations



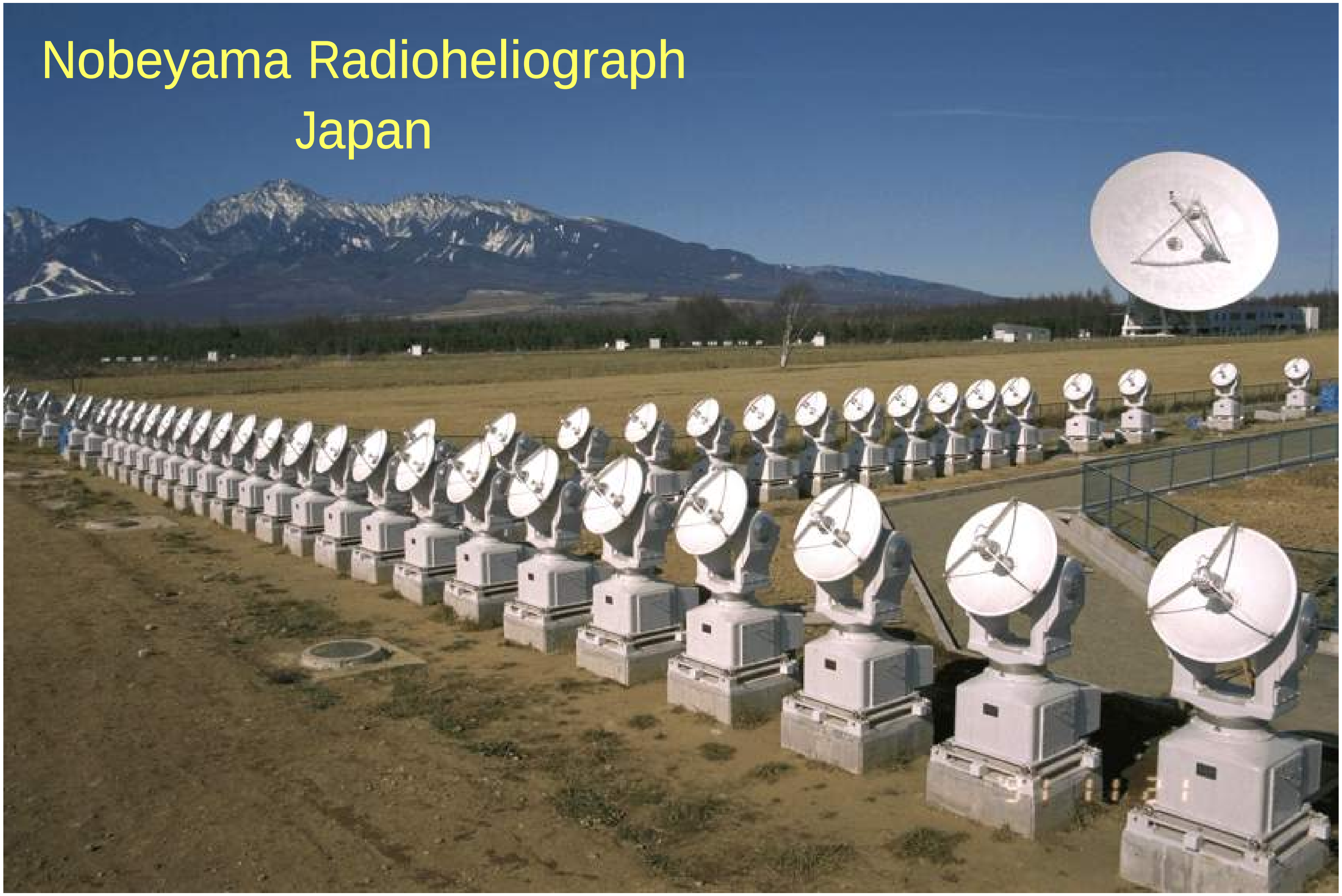
Solar Radio Observations





Wind Waves plus Culgoora

Interferometry



Getting Better Resolution

- A large single dish antenna provides insufficient resolution for modern astronomy.
  - For example, the GBT provides an angular resolution of only 8 arcmin at 1.4 GHz - we want 1 arcsecond or better!
- The trivial solution of building a bigger telescope is not practical. 1 arcsecond resolution at $\lambda = 20$ cm requires a 40 kilometer aperture!
  - E.g., at 1000 ft (305 m), the Arecibo telescope is the largest filled aperture in the world, yet still only yields 3 arcmin resolution!
- As this is not practical, we must consider a means of synthesizing the equivalent aperture, through combinations of elements.
- This method, termed 'aperture synthesis', was developed in the 1950s in England and Australia. Martin Ryle (University of Cambridge) earned a Nobel Prize for his contributions.

Antennas and Arrays

Green Bank Telescope, West Virginia

Antennas and Arrays

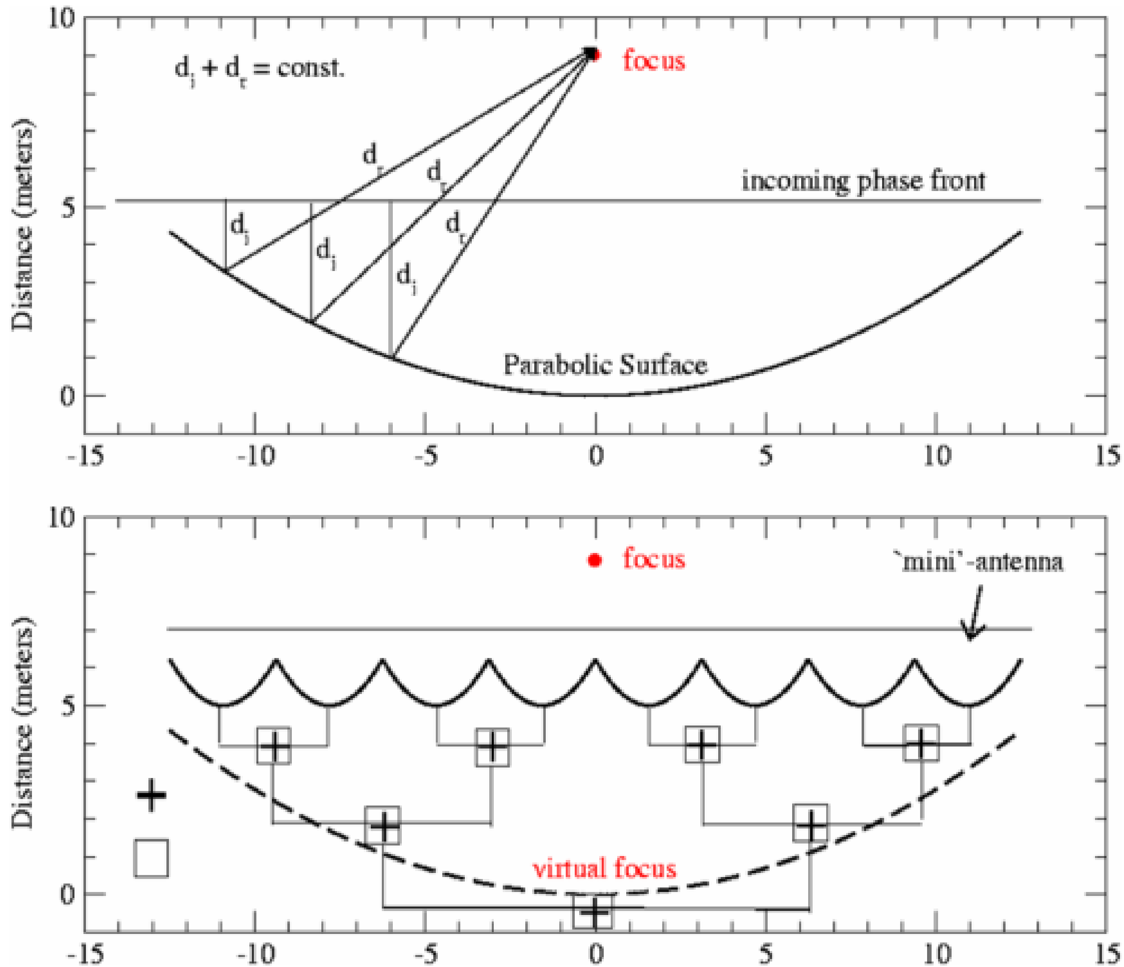
Arecibo Observatory, Puerto Rico

Aperture Synthesis – Basic Concept

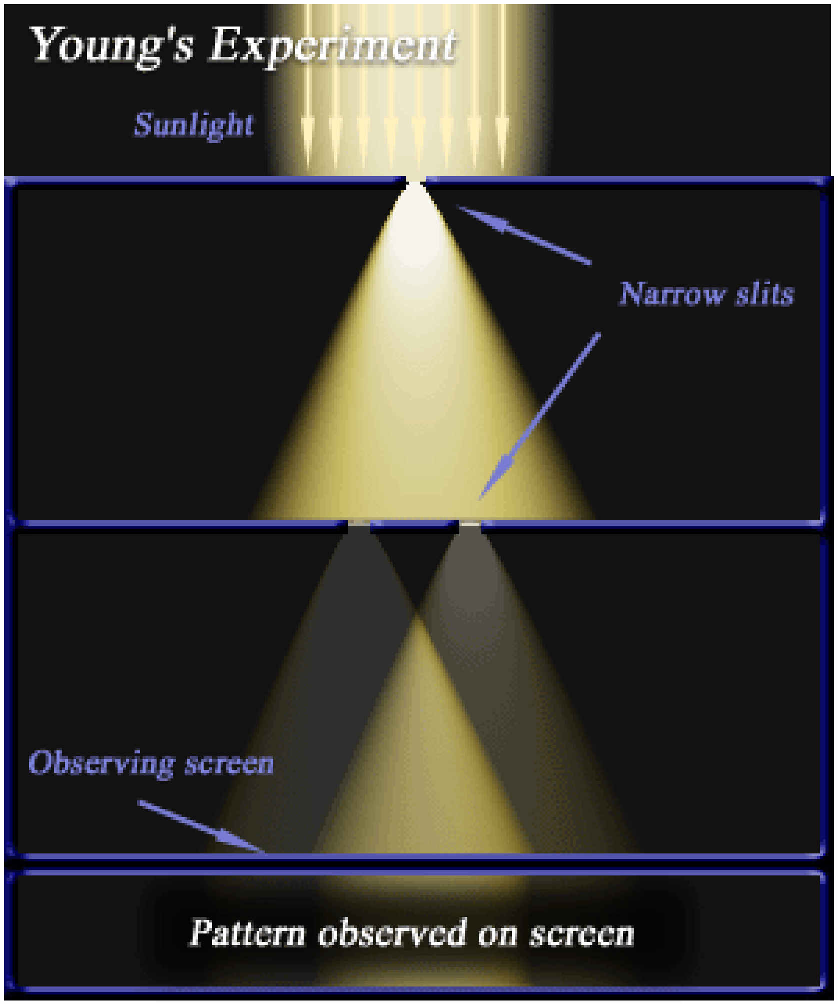
If the source emission is unchanging, there is no need to collect all of the incoming rays at one time.

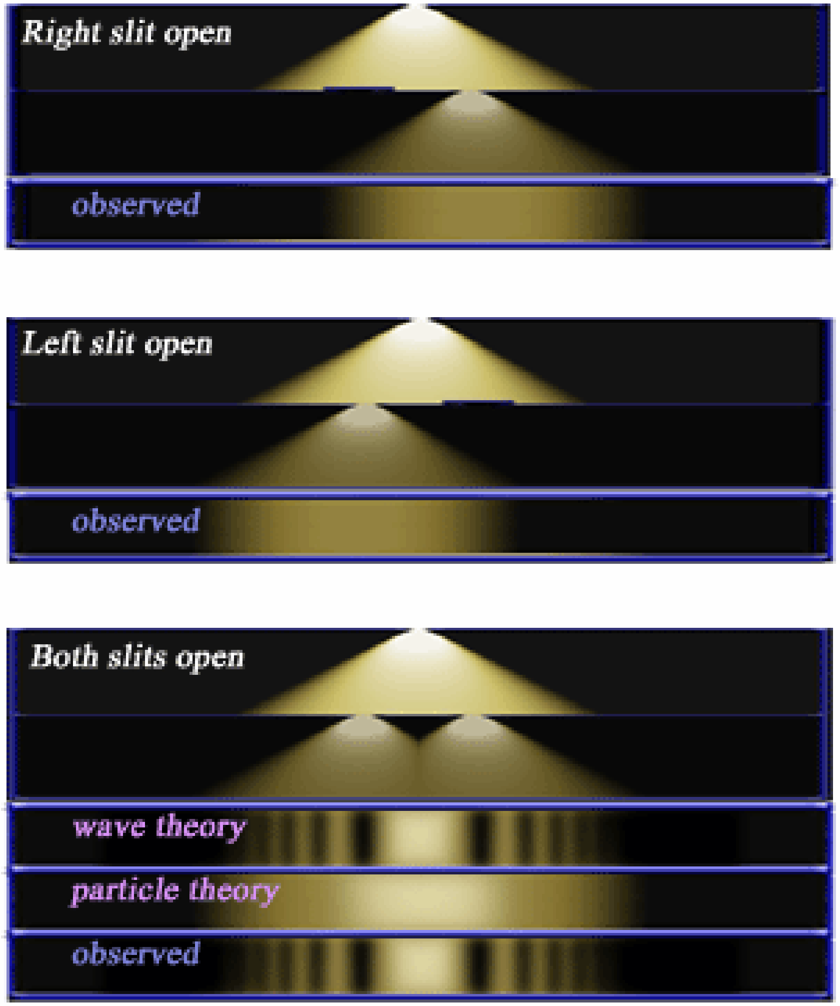
One could imagine sequentially combining pairs of signals. If we break the aperture into N sub-apertures, there will be N(N–1)/2 pairs to combine.

This approach is the basis of aperture synthesis.



Analogy to Young's Two-slit Experiment

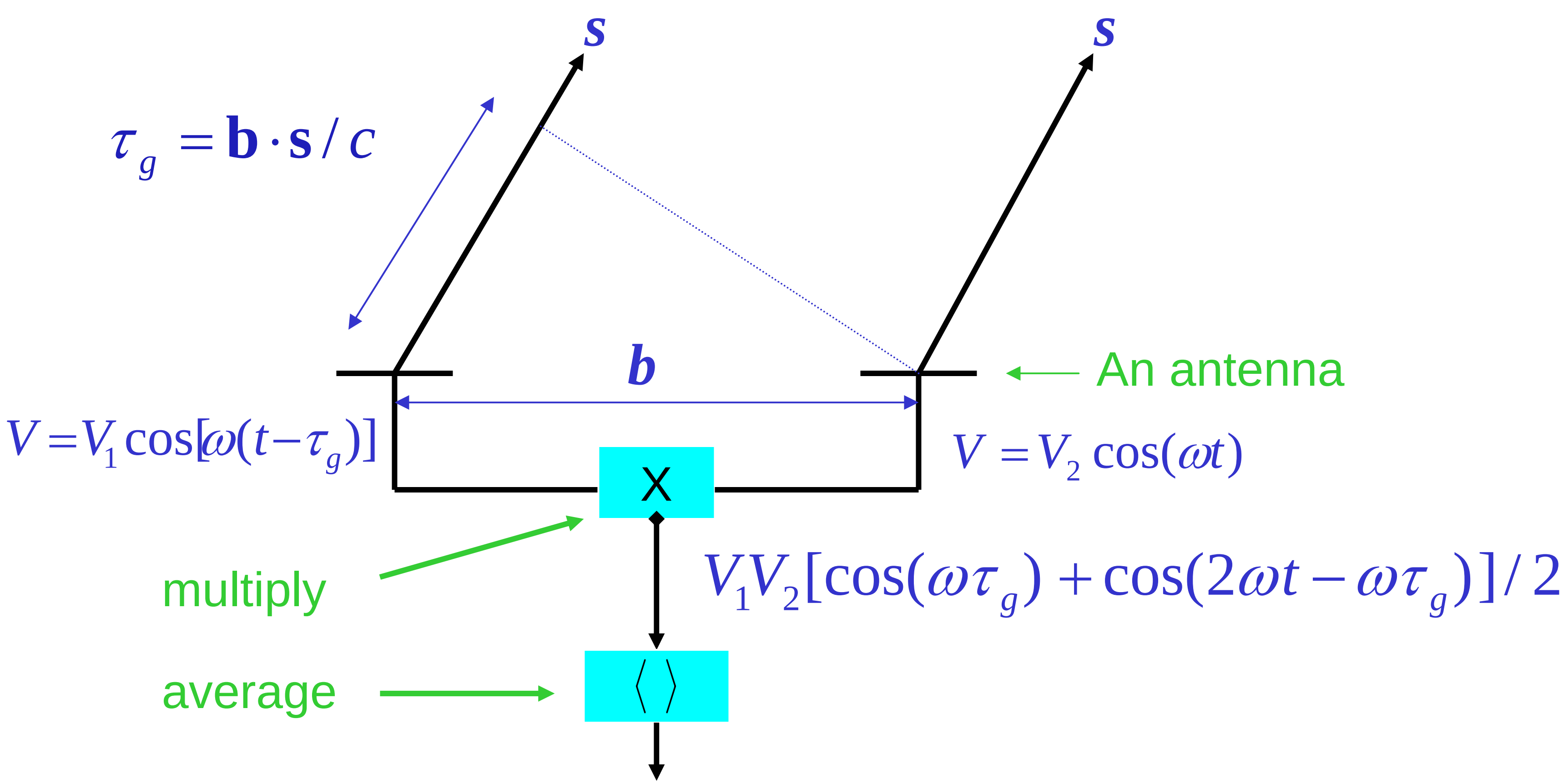




Thomas Young, c.1803

The Stationary, Monochromatic Interferometer

A small (but finite) frequency width, and no motion.
Consider radiation from a small solid angle dΩ, from direction **s**.



$$R_c = [V_1 V_2 \cos(\omega\tau_g)]/2 = [V_1 V_2 \cos(2\pi\nu \mathbf{b} \cdot \mathbf{s} / c)]/2$$

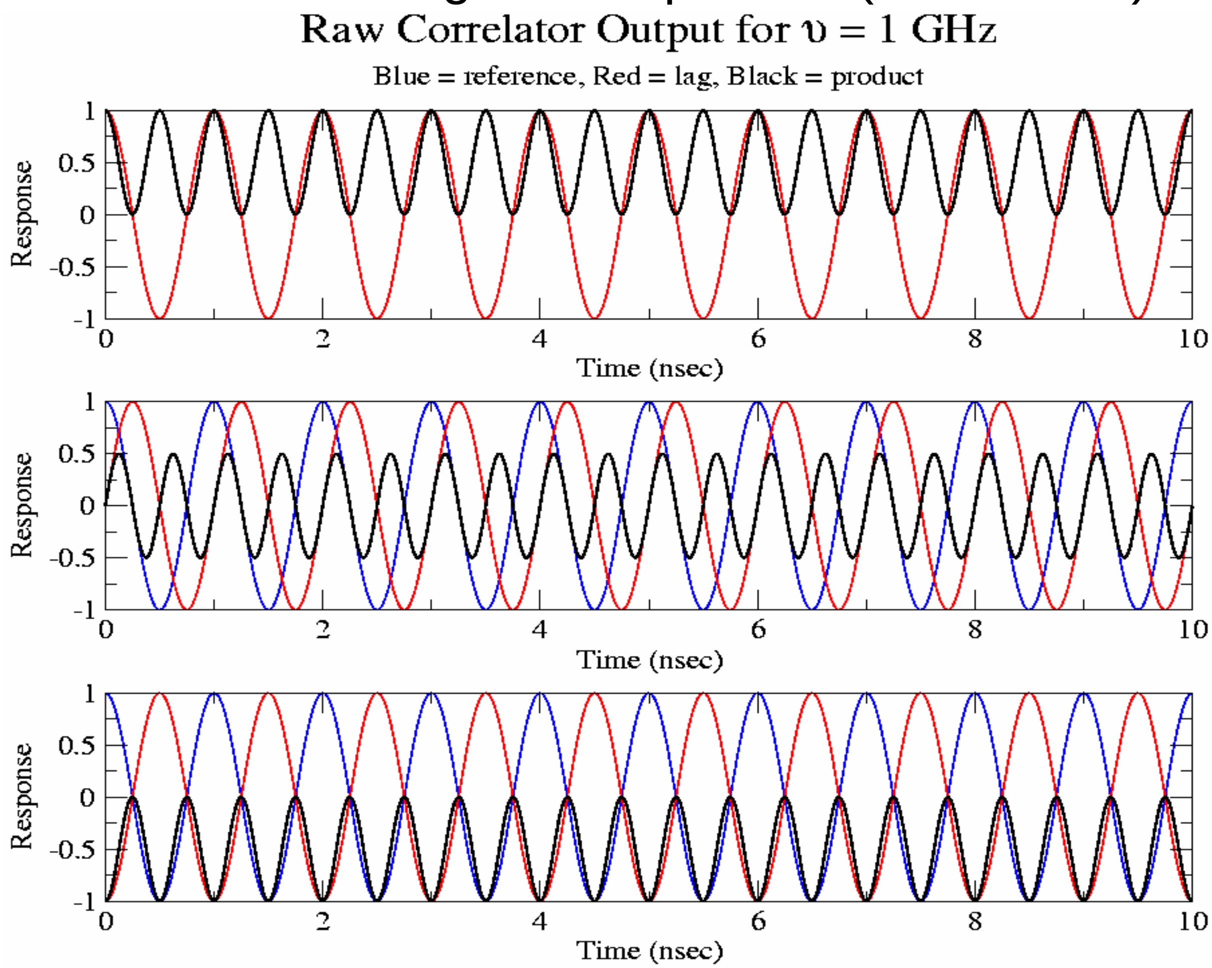
Examples of the Signal Multiplications

The two input signals are shown in red and blue.
The desired coherence is the average of the product (black trace)

In Phase:
$\tau_g = n\lambda/c$

Quadrature Phase:
$\tau_g = (2n+1)\lambda/4c$

Anti-Phase:
$\tau_g = (2n+1)\lambda/2c$



Signal Multiplication, cont.

- The averaged signal is independent of the time t, but is dependent on the lag, τ_g – a function of direction, and hence on the distribution of the brightness.
- In this expression, we use *'V'* to denote the voltage of the signal. This depends upon the source intensity by:

$$V \propto E \propto \sqrt{I}$$

so the term $V_1 V_2$ is proportional to source intensity, I_ν. (measured in Watts m^{-2} Hz^{-1} ster^{-2}).

- The strength of the product is also dependent on the antenna areas and electronic gains – but these factors can be calibrated for.
- To determine the dependence of the response over an extended object, we integrate over solid angle.

The 'Cosine' Correlator Response

- The response from an extended source is obtained by integrating the response over the solid angle of the sky:

$$R_C = \iint I_\nu(\mathbf{s}) \cos(2\pi\nu \mathbf{b} \cdot \mathbf{s} / c) d\Omega$$

where I have ignored any frequency dependence.

Key point: the vector **s** is a function of direction, so the phase in the cosine is dependent on the angle of arrival.

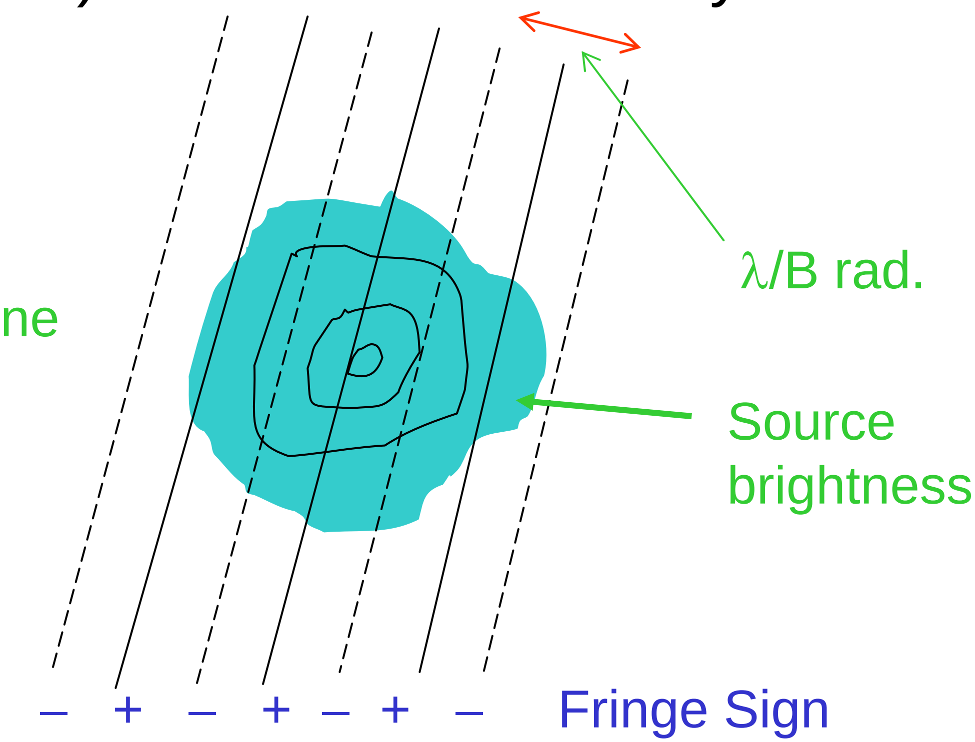
This expression links what we want – the source brightness on the sky) ($I_\nu(\mathbf{s})$) – to something we can measure (R_C, the interferometer response).

A Schematic Illustration

The COS correlator can be thought of ‘casting’ a sinusoidal fringe pattern, of angular scale λ/B radians, onto the sky. The correlator multiplies the source brightness by this wave pattern, and integrates (adds) the result over the sky.

Orientation set by baseline geometry.

Fringe separation set by baseline length and wavelength.

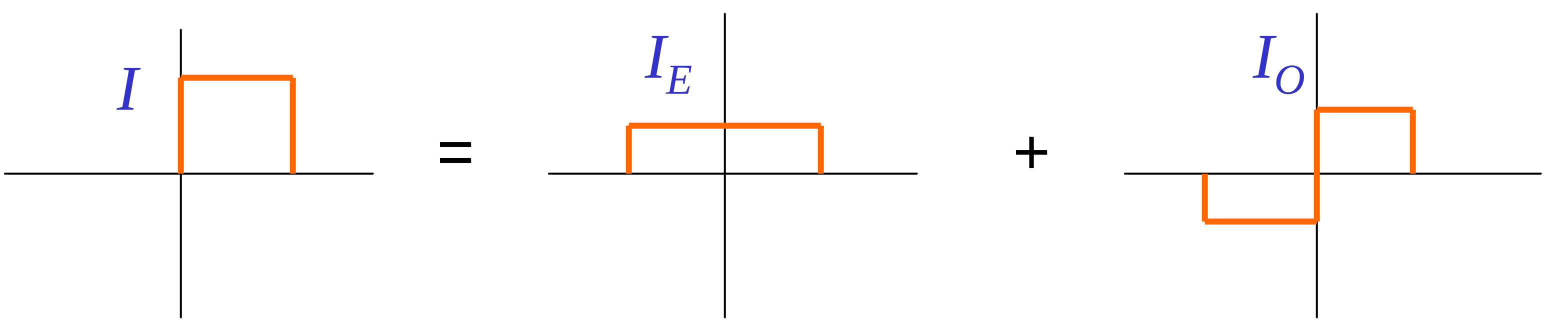


Odd and Even Functions

- But the measured quantity R_c is only sensitive to the 'even' part of the brightness, $I_E(\mathbf{s})$.
- Any real function, I, can be expressed as the sum of two real functions which have specific symmetries:

An even part: $I_E(x,y) = (I(x,y) + I(-x,-y))/2 = I_E(-x,-y)$

An odd part: $I_O(x,y) = (I(x,y) - I(-x,-y))/2 = -I_O(-x,-y)$



Recovering the 'Odd' Part: The SIN Correlator

The integration of the cosine response, R_c, over the source brightness is sensitive to only the even part of the brightness:

$$R_C = \iint I(\mathbf{s})\cos(2\pi\nu\mathbf{b}\cdot\mathbf{s}/c)\,d\Omega = \iint I_E(\mathbf{s})\cos(2\pi\nu\mathbf{b}\cdot\mathbf{s}/c)\,d\Omega$$

since the integral of an odd function (I_O) with an even function ($\cos x$) is zero.

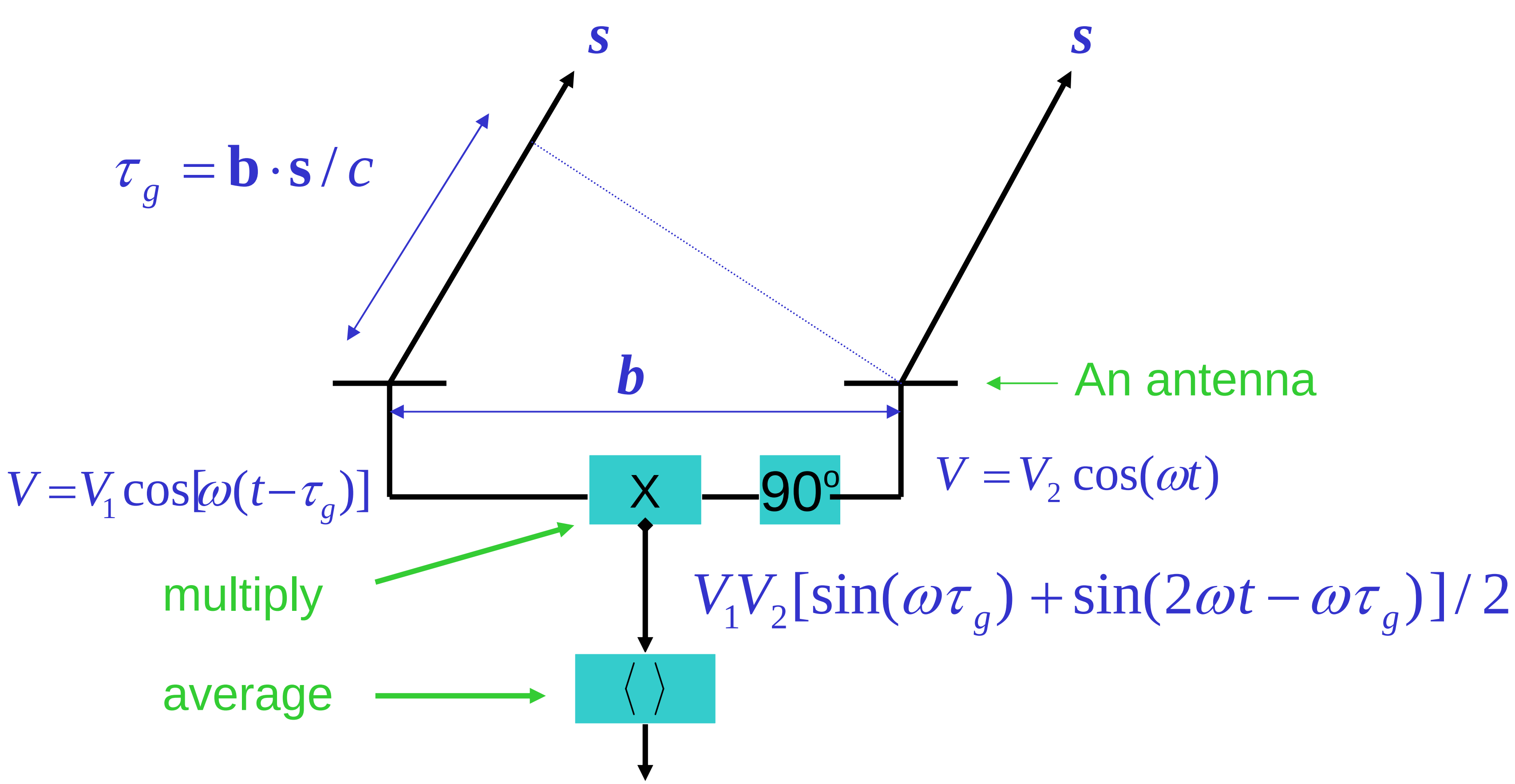
To recover the 'odd' part of the intensity, I_O, we need an 'odd' coherence pattern. Let us replace the '*cos*' with '*sin*' in the integral:

$$R_S = \iint I(\mathbf{s})\sin(2\pi\nu\mathbf{b}\cdot\mathbf{s}/c)\,d\Omega = \iint I_O(\mathrm{s})\sin(2\pi\nu\mathbf{b}\cdot\mathbf{s}/c)\,d\Omega$$

since the integral of an even times an odd function is zero. To obtain this necessary component, we must make a 'sine' pattern.

Making a SIN Correlator

We generate the 'sine' pattern by inserting a 90 degree phase shift in one of the signal paths.



$$R_s = [V_1 V_2 \sin(\omega\tau_g)]/2 = [V_1 V_2 \sin(2\pi\nu \mathbf{b} \cdot \mathbf{s}/c)]/2$$

Define the Complex Visibility

We now DEFINE a complex function, V, to be the complex sum of the two independent correlator outputs:

$$V = R_C - iR_S = Ae^{-i\phi}$$

where

$$A = \sqrt{R_C^2 + R_S^2}$$

$$\phi = \tan^{-1}\left(\frac{R_S}{R_C}\right)$$

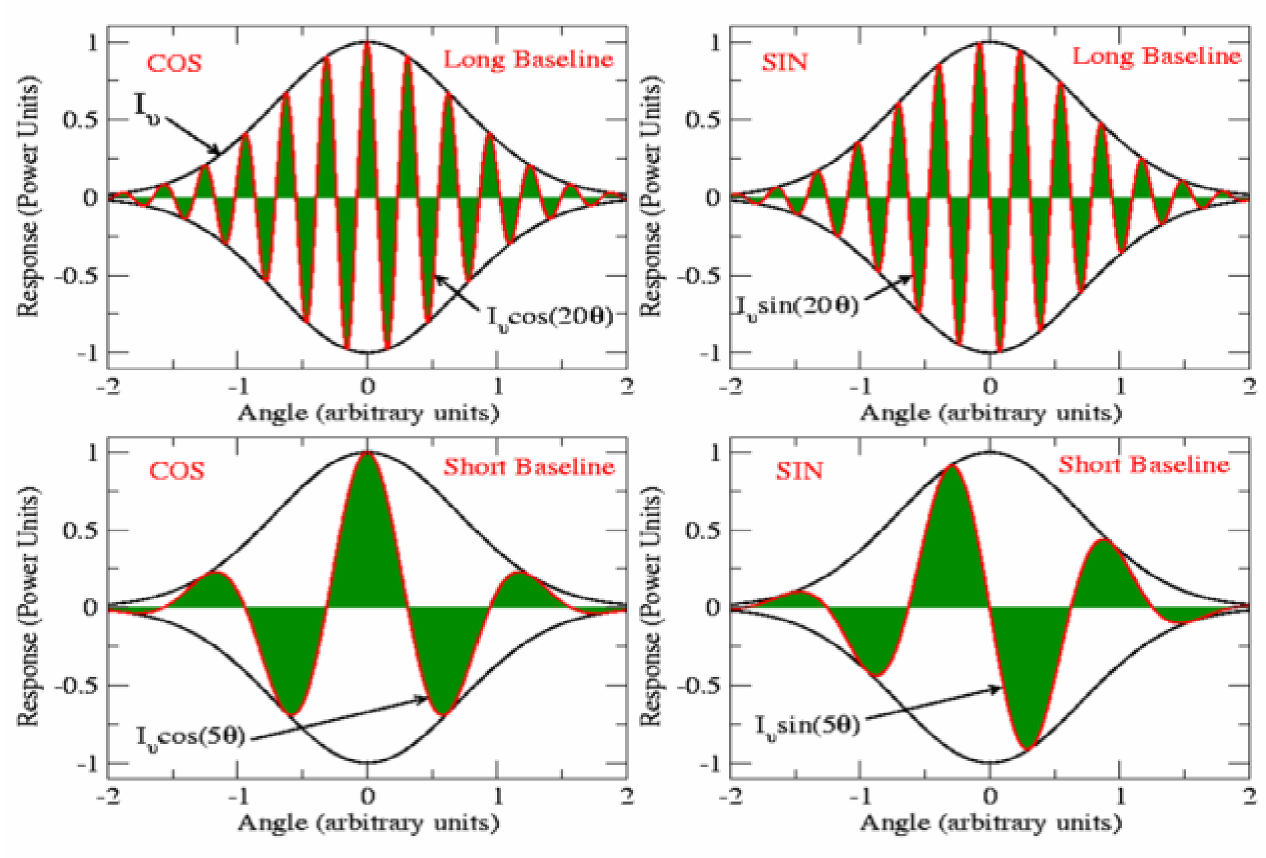
This gives us a beautiful and useful relationship between the source brightness, and the response of an interferometer:

$$V(\mathbf{b}) = R_C - iR_S = \iint I_\nu(s)\, e^{-2\pi i\nu \mathbf{b}\cdot\mathbf{s}/c}\, d\Omega$$

Although it may not be obvious (yet), this expression can be inverted to recover $\mathrm{I}(\mathbf{s})$ from $V(\boldsymbol{b})$.

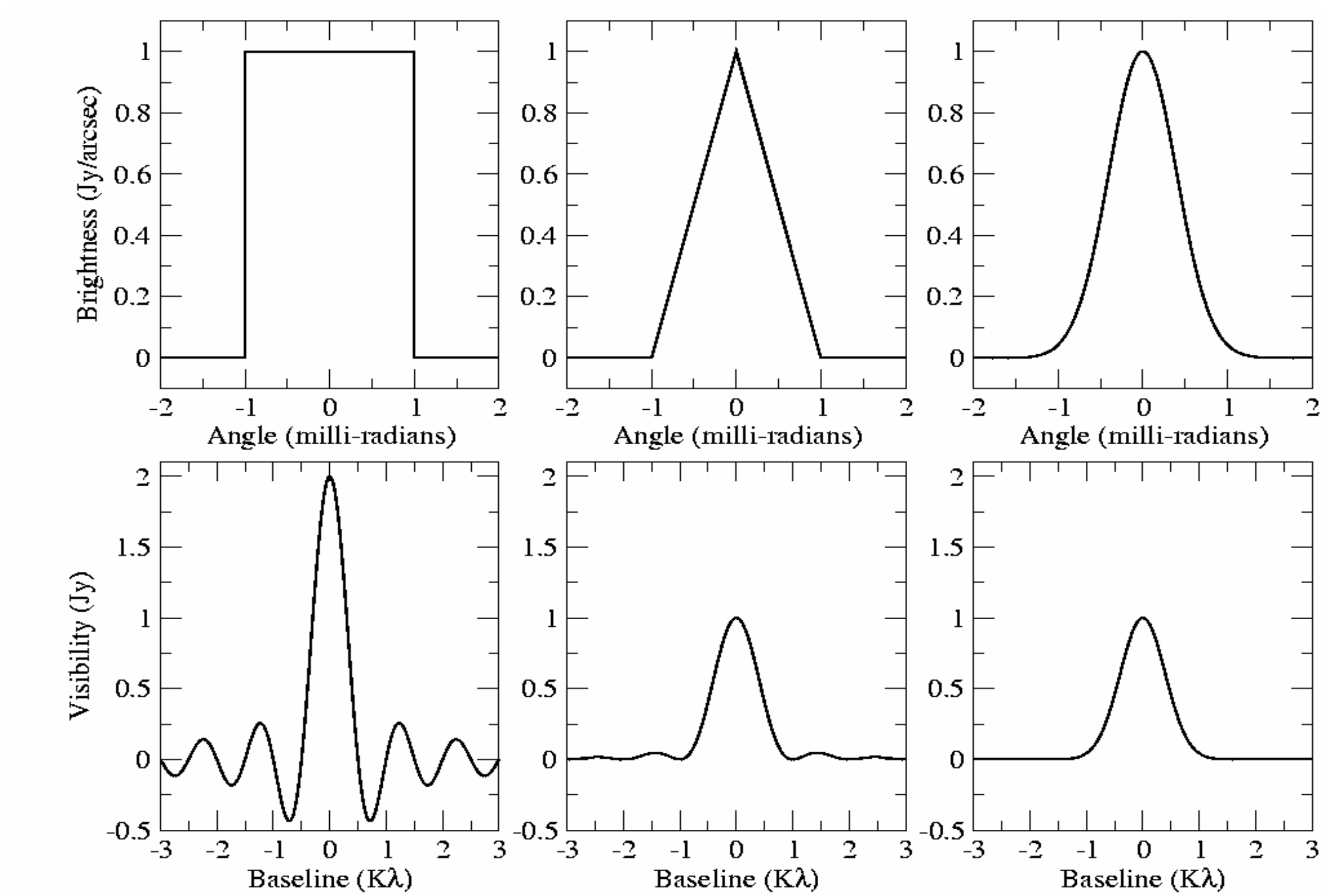
Picturing the Visibility

- The intensity, I_ν, is in black, the 'fringes' in red. The visibility is the net dark green area.



Examples of Visibility Functions

- Top row: 1-dimensional even brightness distributions.
- Bottom row: The corresponding real, even, visibility functions.



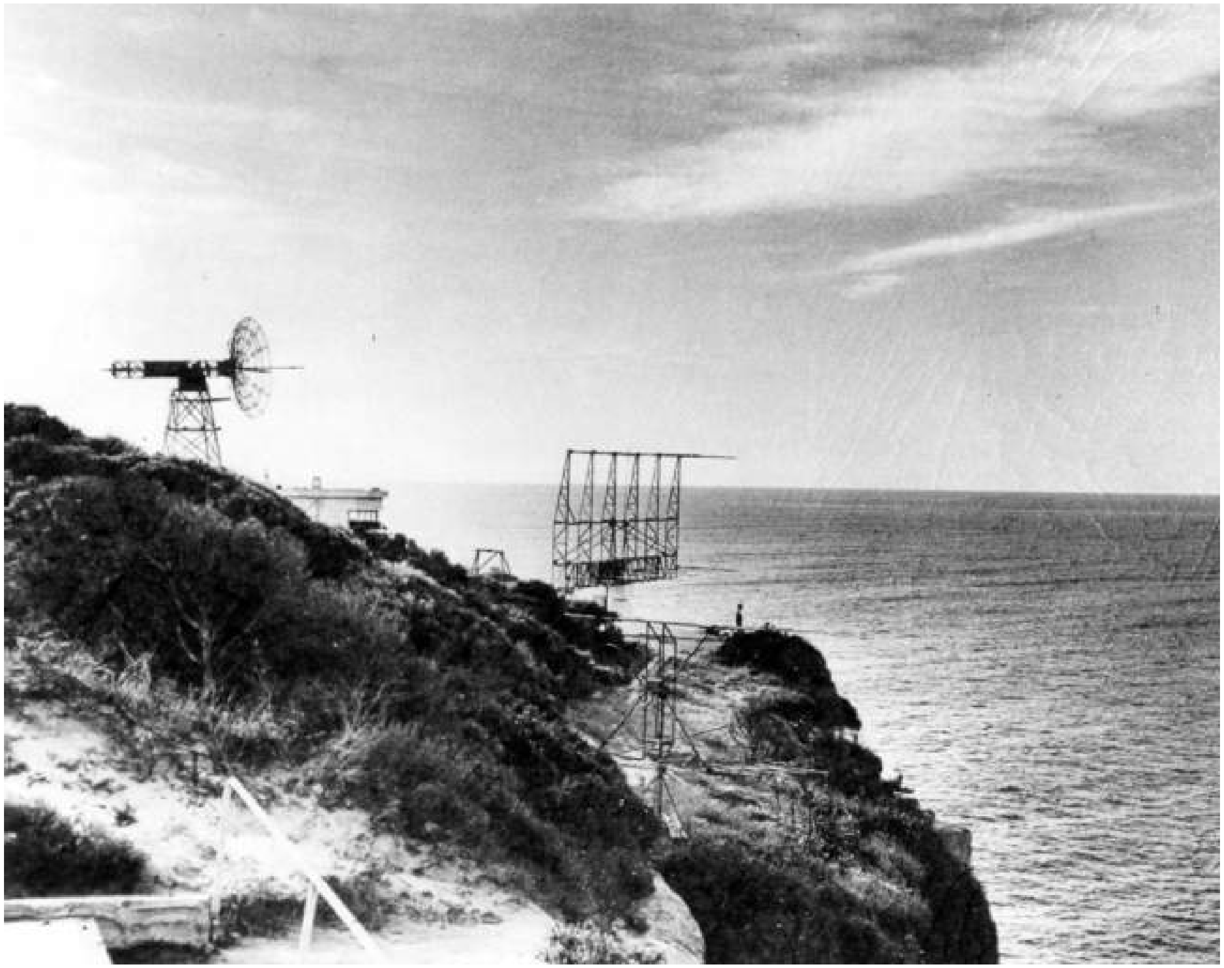
Comments on the Visibility

- The Visibility is a function of the source structure and the interferometer baseline.
- The Visibility is NOT a function of the absolute position of the antennas (provided the emission is time-invariant, and is located in the far field).
- The Visibility is Hermitian: $V(u,v) = V^*(-u,-v)$. This is a consequence of the intensity being a real quantity.
- There is a unique relation (FT) between any source brightness function, and the visibility function.
- Each observation of the source with a given baseline length provides one measure of the visibility.
- Sufficient knowledge of the visibility function (as derived from an interferometer) will provide us a reasonable estimate of the source brightness.

Solar Radio Observations

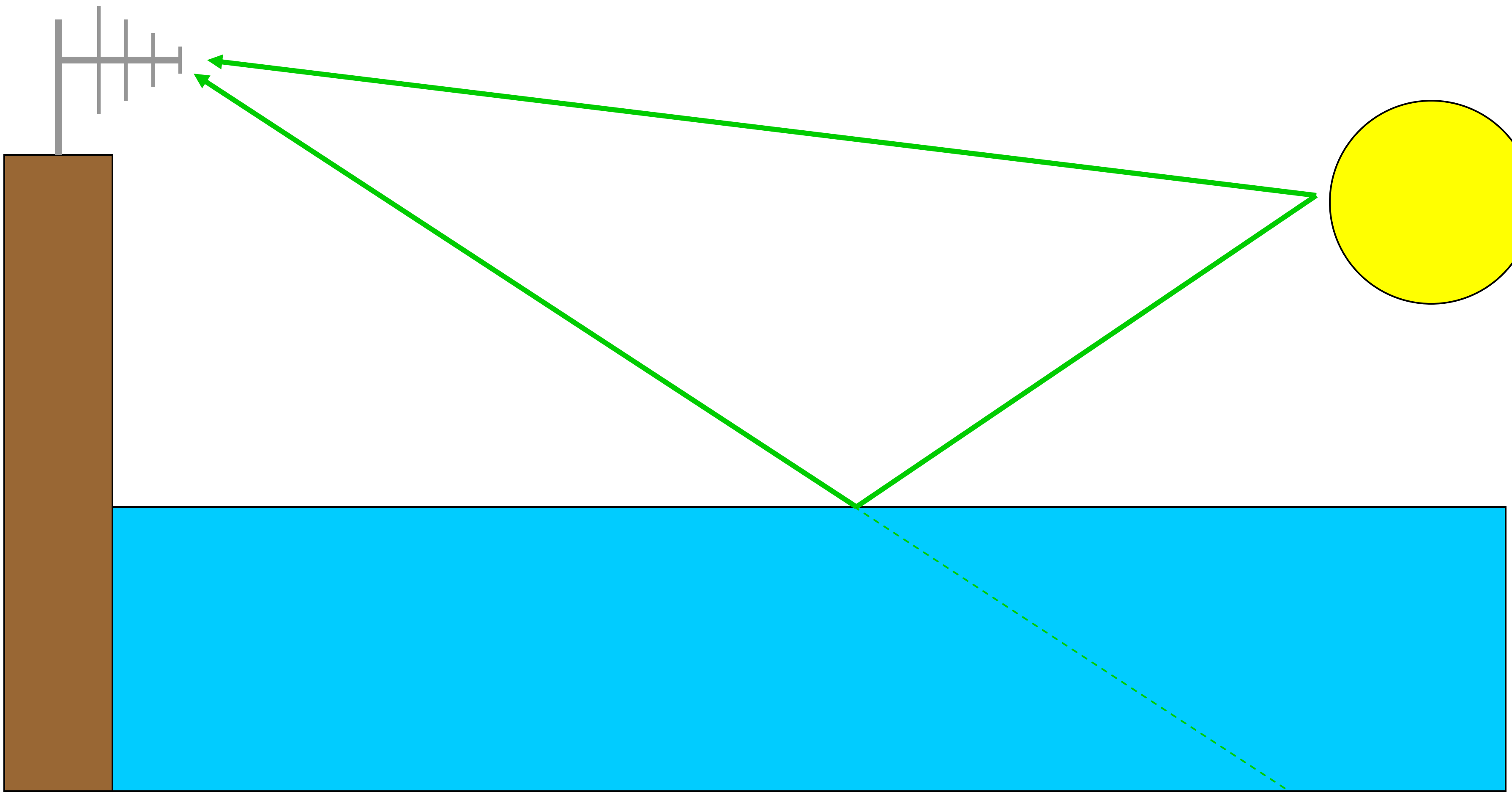
Some Examples

- Cliff interferometer
- Synthesis images
- Snapshot imaging



Dover Heights, NSW Australia

“Cliff Interferometer”



over the sun without further information. It is possible in principle to determine the actual form of the distribution in a complex case by Fourier synthesis using information derived from a large number of components. In the interference method suggested here Δ is a function of h and λ, and different Fourier components may be obtained by varying h or λ. Variation of λ is inadvisable, as over the necessary wide range the distribution of radiation may be a function of wave-length. Variation of h would be feasible but clumsy. A different interference method may be more practicable.

9-2-46

We now return to the special case in which the minima are very deep, i.e. the power is concentrated in a small range of angles, so that we feel justified in quoting the position and width of an equivalent rectangular strip. These quantities have been

McCready, Pawsey, & Payne-Scott 1947

Cliff interferometer

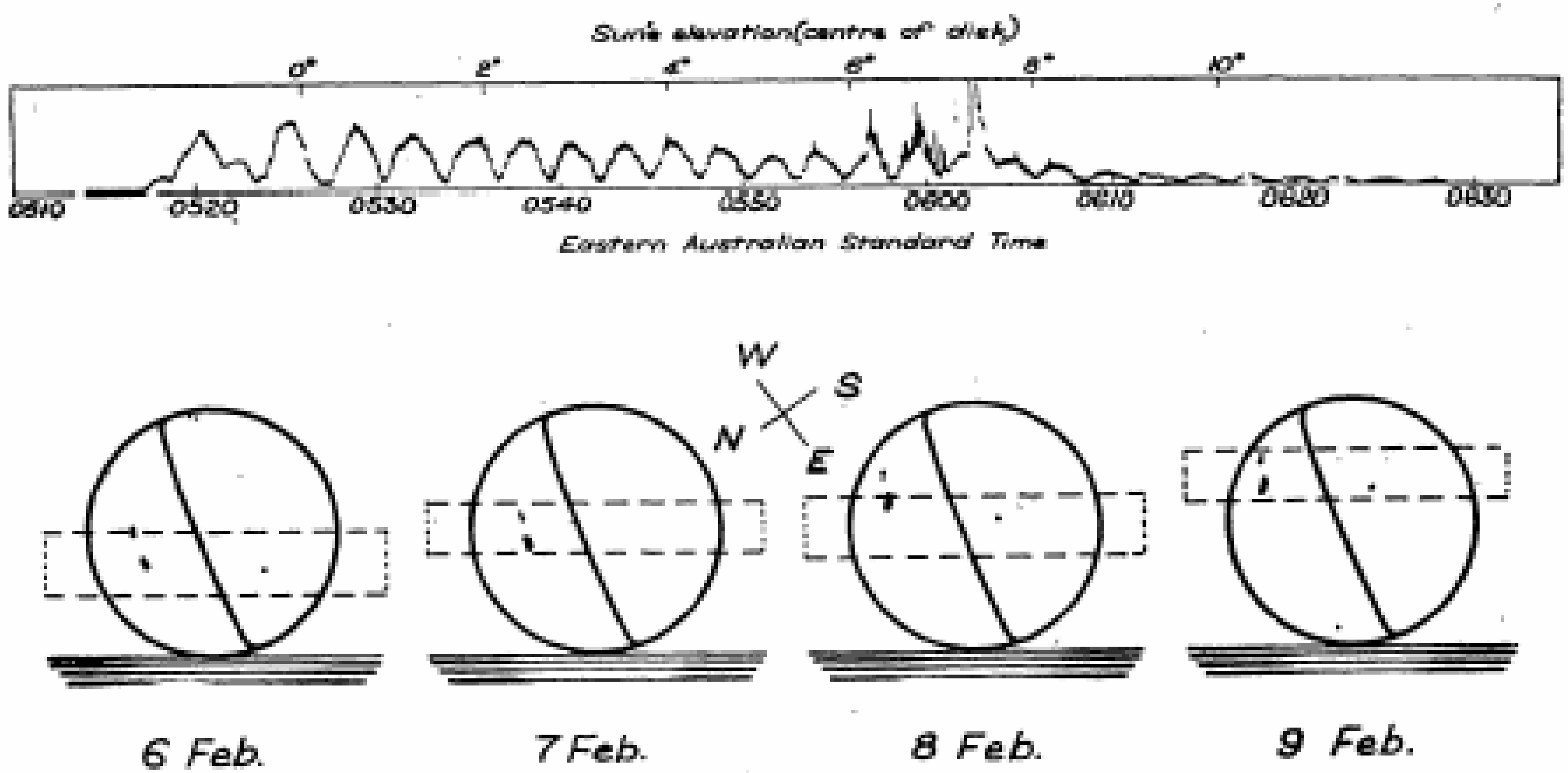


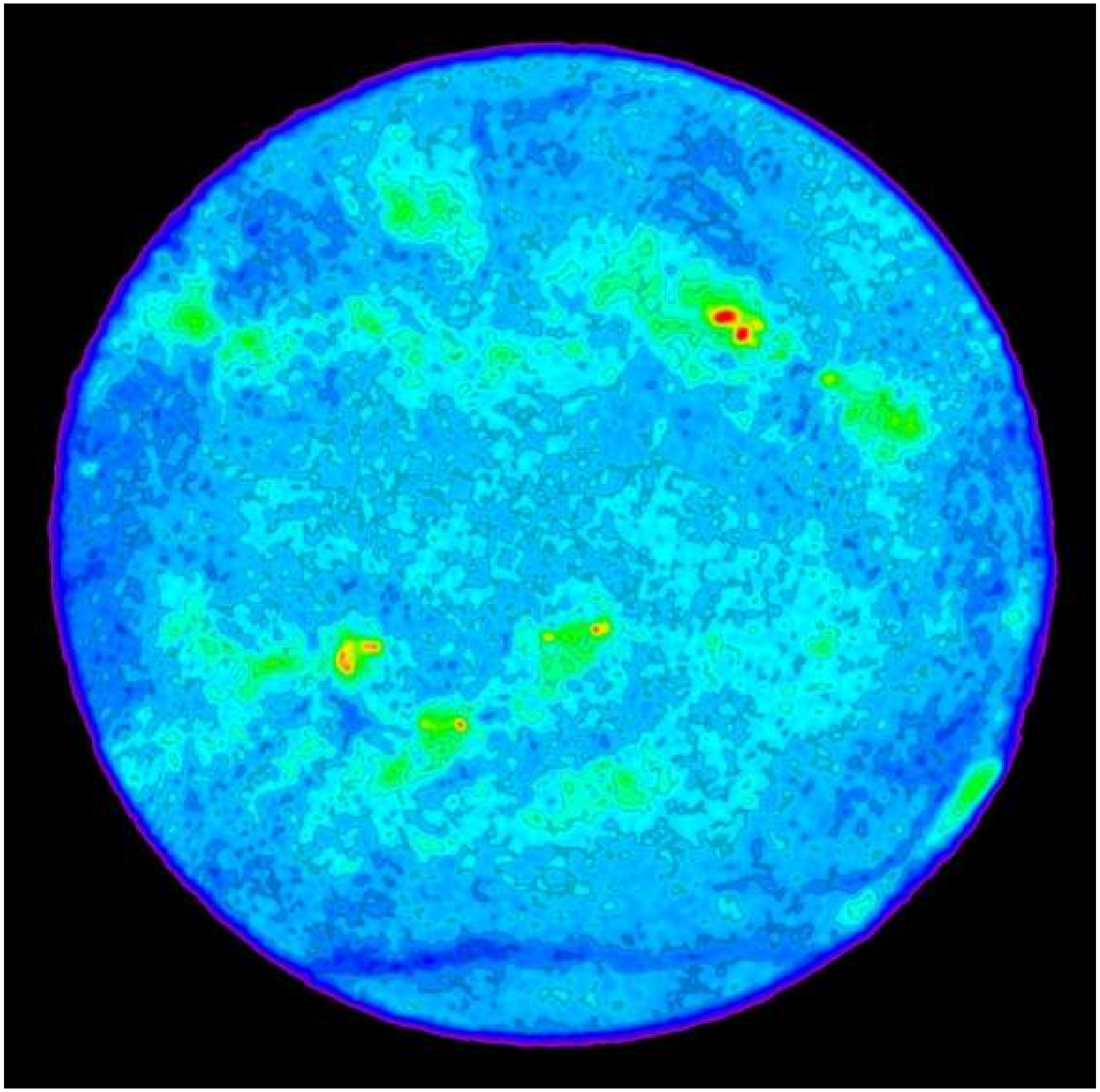
FIG. 4—The first radio-interferometer observations, made during the presence of the great sun-spot of February 1946. (a) One of the records. (b) The deduced position and upper limit to the width of the source of solar radio waves on successive days together with the sun-spot. (McCready, Pawsey and Payne-Scott[2]).

from Pawsey 1953

Very Large Array

Very Large Array

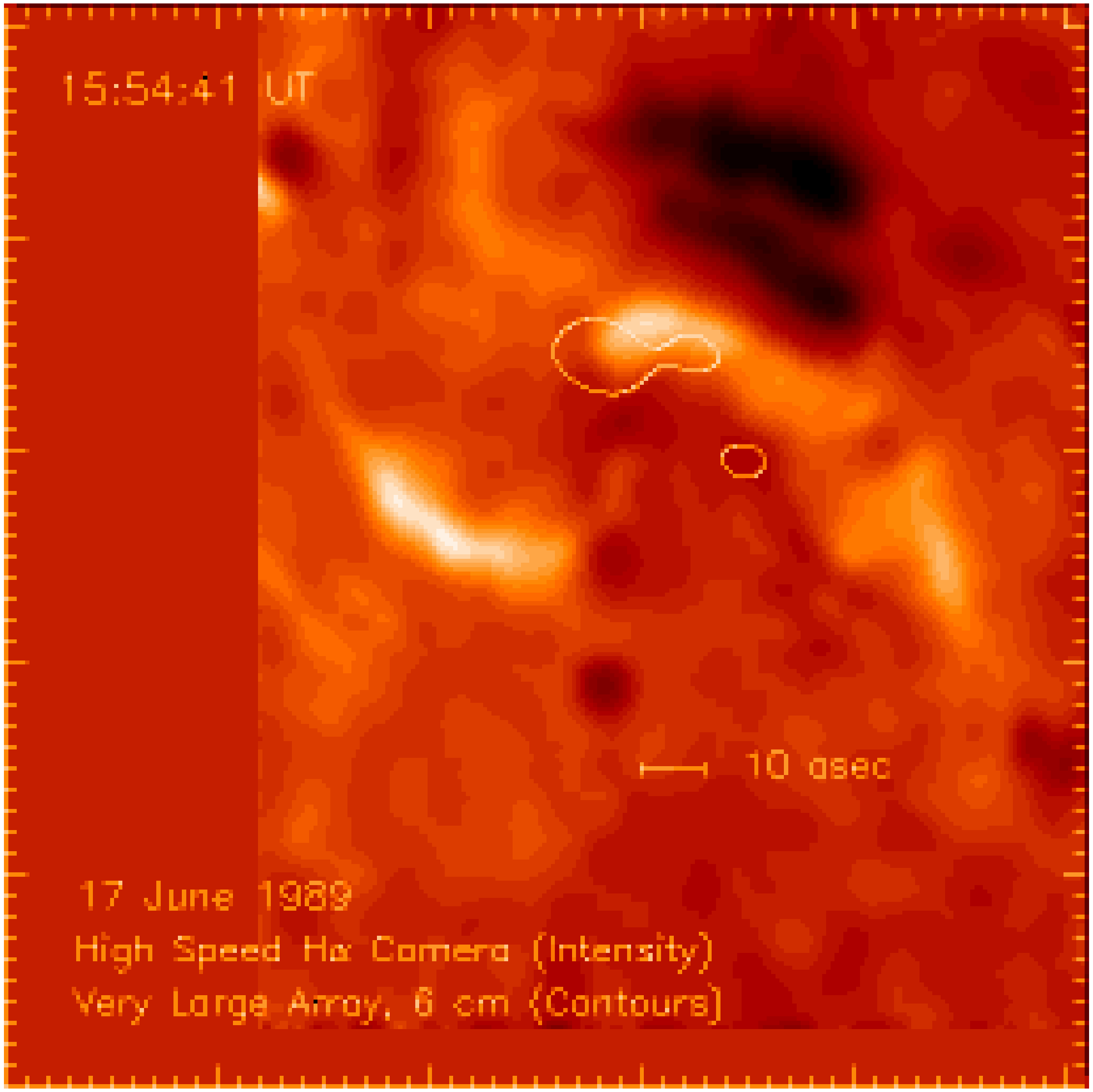
4.9 GHz



T. Bastian, Second SPD Summer School on High Energy Solar Physics

From S. White

Very Large Array



Two ribbon flare observed by the VLA on 17 Jun 89.

6 cm (contours)

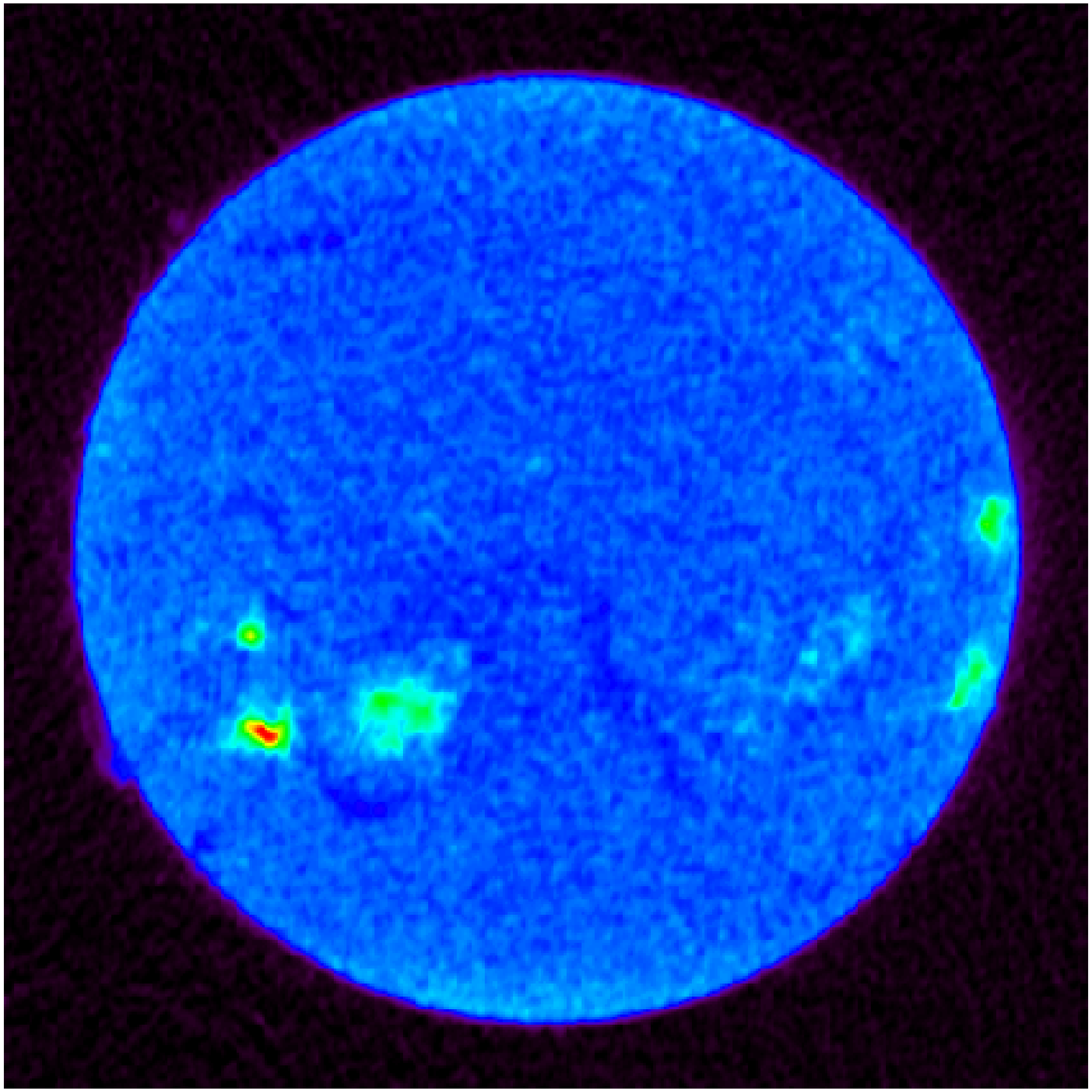
Ha (intensity)

Bastian & Kiplinger (1991)

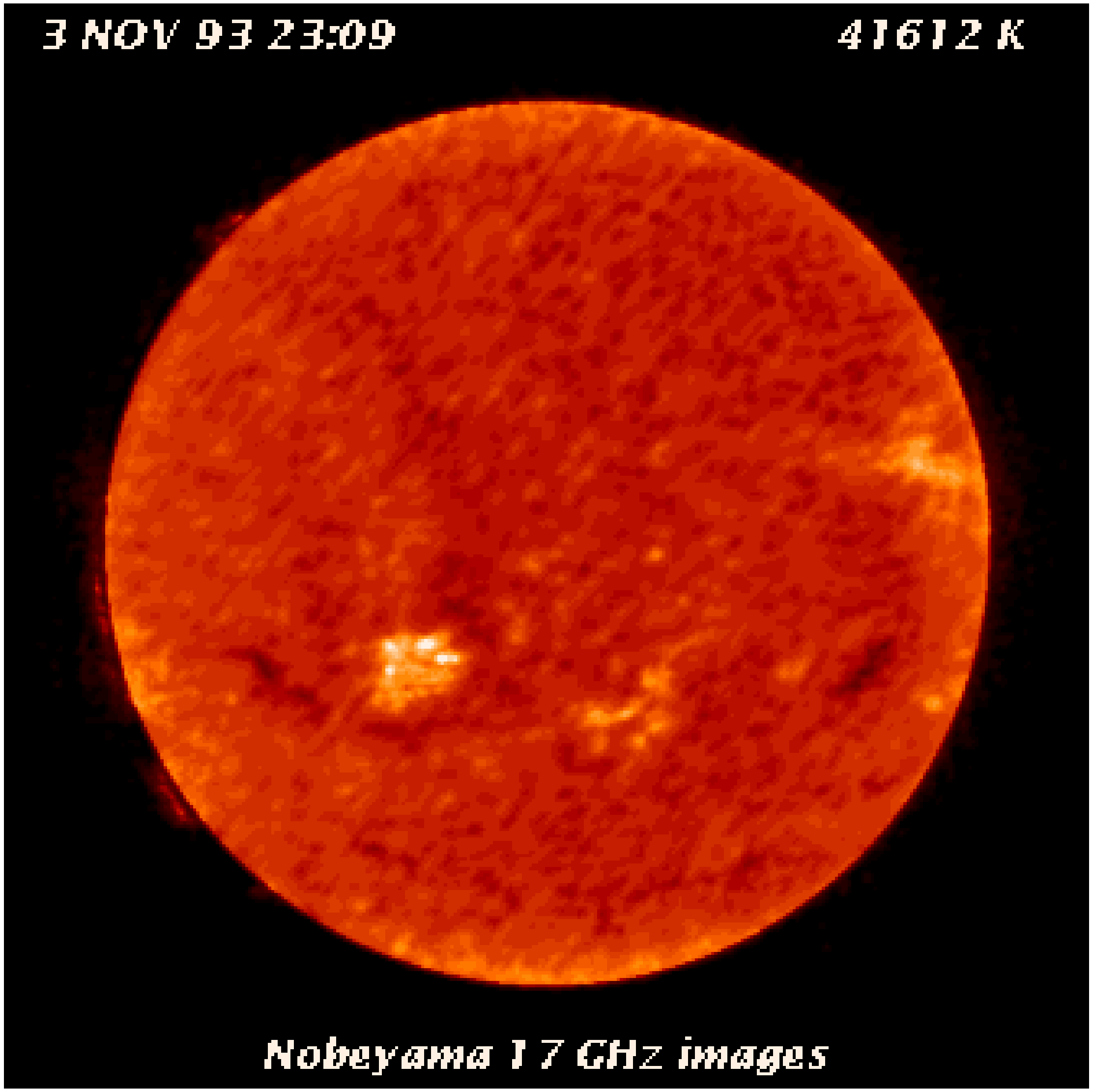
Nobeyama Radioheliograph

Solar Radio Observations

17 GHz



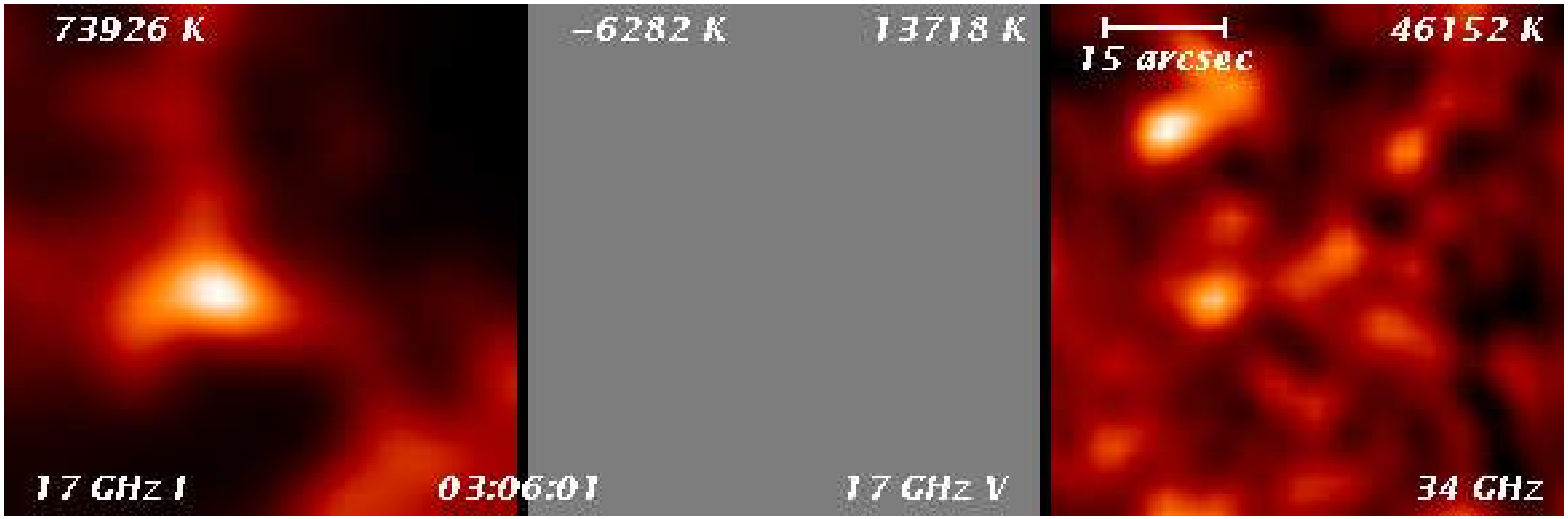
Nobeyama Radioheliograph



From S. White

Nobeyama Radioheliograph

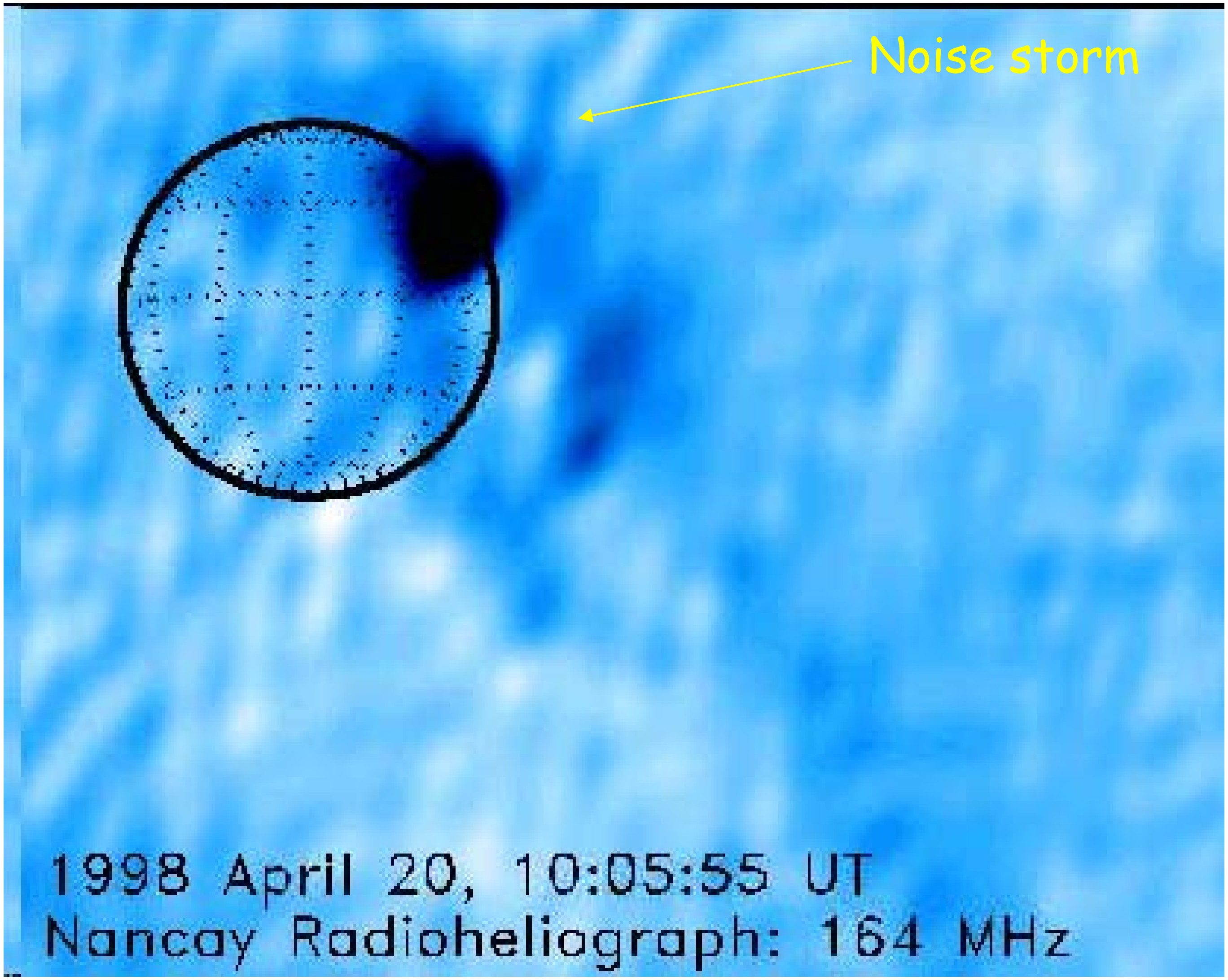
17 GHz intensity | 17 GHz circ. pol. | 34 GHz intensity



Time sequence of snapshot maps and 17 and 34 GHz.

Nançay Radioheliograph

Nançay Radioheliograph



Radio
CME

Bastian et al. (2001)

[redacted]

Observing with the UNH SRT

Antenna Specifications

Diameter	90" (2.3m)
F/D Ratio	0.375
Focal Length	33.75" (85.7cm)
Beam Width	7.0 Degrees

Receiver Characteristics

LO Frequency range	1370-1800 MHz
LO Tuning steps	40 kHz
LO.Settle time	<5 ms
Rejection of LSB image	>20 dB
3 dB bandwidth	40 kHz
IF Center	40 kHz
6 dB IF range	10-70 kHz
Preamp frequency range	1400-1440 MHz
Typical system temperature	150K
Typical LO leakage out of preamp	-105dBm
Preamp input for dB compression from out of band signals	-24 dBm
Preamp input for intermodulation interference	-30 dBm
Square law detector max.	4000 K a 0 dB attenuation 40,000 K at 10 dB attenuation
Control	RS-232 2400 baud

Radiometer Equation

- For an unresolved source, the detection sensitivity of a radio telescope is determined by the effective area of the telescope and the "noisiness" of the receiver
- For an unresolved source of a given flux, S_ν, the expected antenna temperature is given by

$$T_A = ½\, A_{eff} S_\nu / k_B$$

- The minimum detectable δT_A is given by

$$\delta T_A = \beta T_{sys} / \sqrt{(\Delta\nu\tau)}$$

where T_{sys} is the system temperature of the receiver, $\Delta\nu$ is the bandwidth and τ is the integration time, and β is of order unity depending on the details of the system. The system temperature measures the noise power of the receiver ($P_s = \Delta\nu k_B T_s$). In Radio Astronomy, detection is typically receiver noise dominated.

Calibration

Calibration of an instrument involves establishing by means of measurement and/or comparisons with “known” quantities the correspondence between the instrument output and the desired observable in physically meaningful units.

Calibration usually requires a detailed understanding of all instrumental and external factors that may effect the signal.

Calibration

Antenna beam (power pattern)

- Figure of reflector
- Illumination
- Blockage
- Spillover

Antenna pointing

- Gravity
- Wind
- Temperature
- Mechanical

Antenna FE electronics

- Gains and losses
- Linearity of components

Atmosphere

- Emission & absorption
  - o Temperature
  - o Pressure
  - o humidity

Ground

Radio Frequency Interference

Galactic/other background

Spectral baselines

- Properties of spectrometer
- Filter response

Calibration

A common and effective means of calibrating the gain of a single dish is to compare observations on the source and on the empty sky with observations of a "load at ambient temperature".

How does this work?

By a "load at ambient temperature" we mean a piece of absorbing material that is at the same temperature as the surrounding atmosphere and ground. The load is placed directly in front of the feed so that when it is in place, the system only sees noise contributions due to the load and the receiver:

$$T_{rx} + T_{abs}$$

Calibration

When we remove the load and observe the "empty" sky we have

$$T_{rx} + T_{sky}(1 - e^{-\tau})$$

The ratio of the two signals is

$$y = \frac{T_{rx} + T_{abs}}{T_{rx} + T_{sky}(1 - e^{-\tau})}$$

Assuming $T_{abs} = T_{sky} = T$ we have

$$y - 1 = \frac{T_{rx} + T - [T_{rx} + T(1 - e^{-\tau})]}{T_{rx} + T(1 - e^{-\tau})} = \frac{Te^{-\tau}}{T_{rx} + T(1 - e^{-\tau})}$$

Calibration

$$\frac{T_{abs}}{y-1} = \frac{T}{y-1} = [T_{rx} + T(1-e^{-\tau})]e^{\tau} = T_{sys}$$

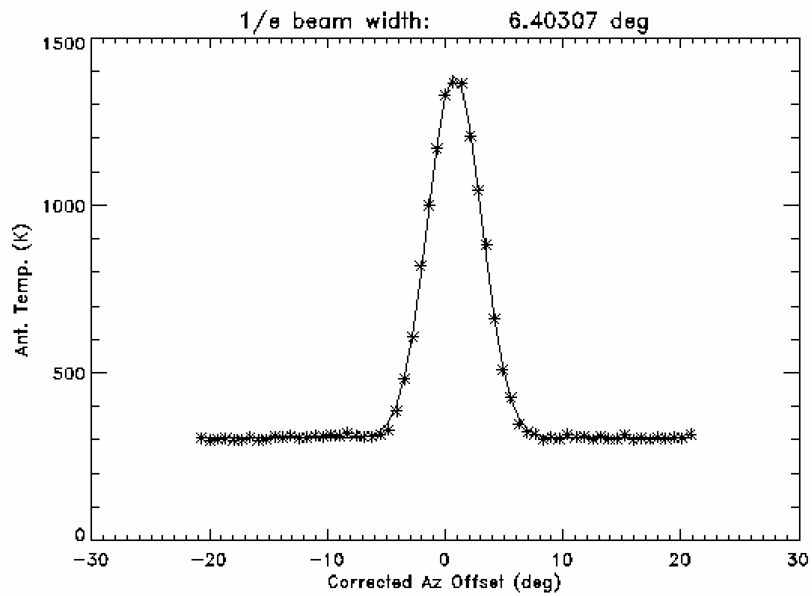
We can now calibrate an observation of a source by “beam switching”. First, observe the source (ON position), yielding

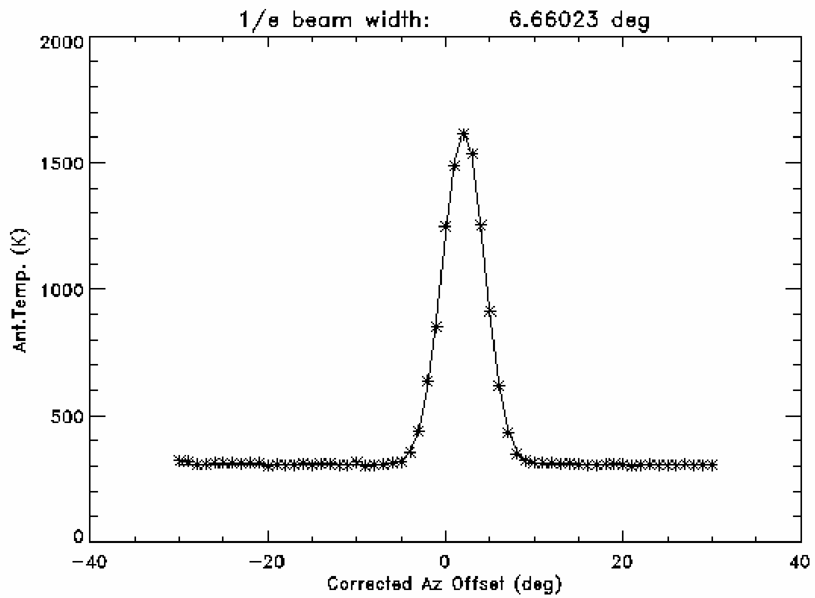
$$T_a + T_{rx} + T_{sky}(1-e^{-\tau}) = T_a^{'}e^{-\tau} + T_{rx} + T_{sky}(1-e^{-\tau})$$

Next, observe blank sky near the source so that the atmospheric conditions are similar (OFF position):

$$T_{rx} + T_{sky}(1-e^{-\tau})$$

$$\left[\frac{ON-OFF}{OFF}\right]T_{sys} = \frac{T_a^{'}e^{-\tau}}{T_{rx} + T(1-e^{-\tau})}T_{sys} = T_a^{'}$$


1/e beam width: 6.40307 deg
Ant. Temp. (K)
Corrected Az Offset (deg)


1/e beam width: 6.66023 deg
Ant.Temp. (K)
Corrected Az Offset (deg)

[redacted]

Historical background

Heinrich Hertz (1857-1894)

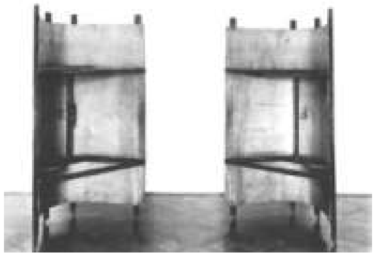
Hertz was born in Hamburg. Studying under Kirchoff and Helmholtz, Hertz obtained his degree in 1880. He went on to become lecturer at the University of Kiel in 1883. There he began his studies of Maxwell's theory of electromagnetic fields.

In 1885 he was appointed professor of physics at the Karlsruhe Technical College of Berlin. It was there that he conducted his famous experiments that validated Maxwell's theory in 1888.

He went on to become a professor at the University of Bonn in 1889. Tragically, he contracted a bone disease in 1892 and then died in 1894.

Historical background

Hertz's main accomplishments were:

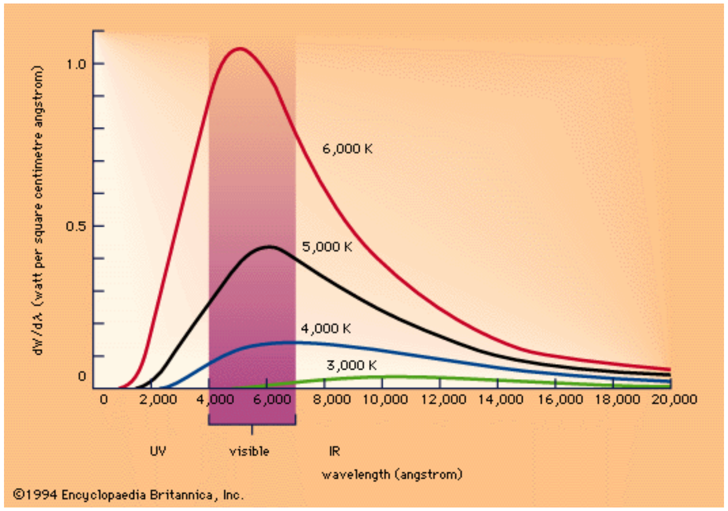


- demonstrating the existence of electromagnetic waves
- demonstrating that they were at long wavelengths
- demonstrating that they, like visible light, could be reflected, refracted, could interfere with each other, and were polarized

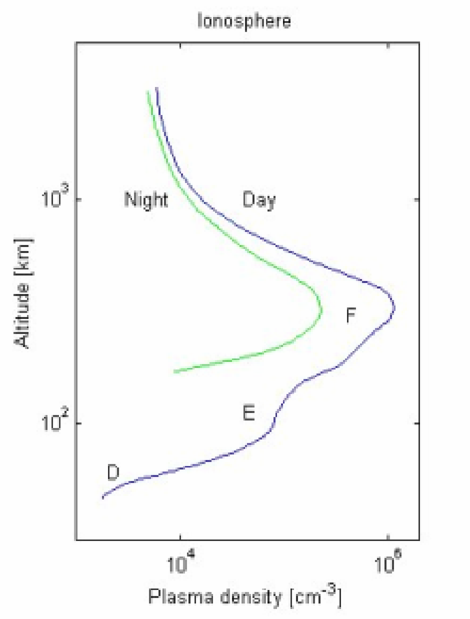
Commenting on his discovery, Hertz is alleged to have said: *"It's of no use whatsoever. This is just an experiment that proves Maestro Maxwell was right – we just have these mysterious electromagnetic waves that we cannot see with the naked eye. But they are there."*

Historical background

Two factors perhaps led to a loss of interest in the possibility of detecting radio waves from the Sun:



The hard realities of the Planck curve (1900).



The prediction of the ionosphere (1902), confirmed in the 1920s.

But that did not mean interest in radio waves disappeared. On the contrary, practical applications of radio waves were immediately recognized and developed.

Historical background

While Hertz may not have been seen further possibilities for his "Hertzian waves", others saw both scientific and commercial possibilities:

Scientific interest focused on the Sun:

Thomas Edison suggested in 1890 that the Sun might be detectable at long wavelengths and proposed an experiment to do so.

Sir Oliver Lodge actually tried to detect the Sun in 1894 but was unsuccessful.

Johannes Wilsing and Julius Scheiner were the first to actually attempt detection of the Sun and to formally write up their results for a scientific journal in 1896.

Charles Nordman also attempted to detect the Sun from high on Mont Blanc in 1900. In retrospect, this attempt should

Historical background

Guglielmo Marconi (1874-1937)

Historical background

Marconi was born in Bologna in 1874 the product of a wealthy Italian landowner, Giuseppe Marconi, and Annie Jameson (of Jameson Irish Whiskey!).

Marconi learned of Hertz's groundbreaking experimental work at the time of Hertz's death in 1894. He immediately thought of the possibility of using electromagnetic waves to transmit signals. He began experimenting with wireless transmission of signals and, in 1896, filed patents for the first wireless telegraphy system and founded the Wireless Telegraph & Signal Company in 1897.

[Note: Lodge was actually the first to transmit wireless telegraphy, but considered it merely an academic exercise.]

The next few years saw rapid technical innovation that greatly increased the range of wireless communication. Marconi became the first to perform a wireless transmission and detection across the Atlantic Ocean in 1901.

Wireless grew in leaps and bounds thereafter making Marconi and his company rich and influential.

Historical background

It was not until the 1930s that scientific interest in radio waves was renewed, and only because a young engineer with Bell Telephone was tasked with investigating sources of noise in transatlantic radio communications.

Karl Jansky (1905-1950) built an antenna that operated at 14 m and, after making observations for several months, identified two types of noise:

- *Local and more distant thunderstorms*
- *A faint, steady hiss of unknown origin*

Further work showed that the latter did not repeat every 24h, as might be expected for a terrestrial source, but every 23h 56m! Jansky demonstrated that the source of the noise was toward Sagittarius, the center of the Milky Way. His results were reported in the New York Times in May, 1933.

While Jansky wanted to continue his investigations, Bell Lab had its answer and moved him to other pursuits. He never returned to radio astronomy. Nevertheless, the fundamental unit of radio flux bears his name:

$$1 \text{ Jansky} = 10^{-26} \text{ Watts m}^{-2} \text{ Hz}^{-1}$$

Historical background

The Sun was finally detected during WW II. Both J. S. Hey and, independently, G. Southworth (1942) discovered radio emission from the Sun as part of their investigations of potential jamming of radar stations by the Germans.

Their discoveries were suppressed until after the war for security reasons.

WW II played a major role in finally jumpstarting radio astronomy as an independent scientific discipline. The war resulted in a great many radio and radar engineers.

Stimulated by discoveries by Jansky, Reber, Southworth, and Hey – coupled with the availability of trained personnel - radio astronomy leaped forward after the War.

Historical background